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CONTENTS.

MAPS.

ERRATA.

On page 8, fifteenth line from top, for "are" read *is*.

" 33, thirteenth line from top, for "is" read *are*.

" 33, twentieth line from top, for "axis appears" read *axes appear*.

" 33, twenty-first line from top, for "it" read *the axial plane*.

" 33, fourth and thirteenth lines from bottom, for "axis" read *axes*.

" 195, twenty-first line from top, for "serpentized" read *serpentinized*.

" 397, twenty-third line from top, for "applicable" read *appreciable*.

" 404, eighth line from bottom, for "hypothesis" read *hypotheses*

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THE GEOLOGY OF CARMELO BAY.

BY

ANDREW C. LAWSON,

With Chemical Analyses and Coöperation in the Field Work by

JUAN DE LA C. POSADA.

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THE GEOLOGY OF CARMELO BAY.

INTRODUCTION.

THERE are several references to the rocks of Carmelo Bay, or its immediate vicinity, in the literature of the geology of California. No statement can, however, be found which clearly sets forth, in a connected discussion, the relations which may there be observed. Many of the single observations which have been made are correct and valuable in themselves, but they are for the most part incomplete and unsatisfactory records; and inferences have been drawn which, if correct, would have a very important bearing on the entire geology of the Pacific Coast, but which, according to our own observations, are entirely erroneous, and therefore should be corrected.

The circumstance which attracted the attention of the writer to this locality was the description by Whitney in his Geology of California, Vol. I, of the intrusion of granite into the Miocene strata and the consequent alteration of the latter at the contact. This was deemed a very important fact in the geology of this coast, and as the locality was easily accessible, the writer, shortly after his arrival in California, conducted a class of students to the place, Whitney's volume in hand, with the object of demonstrating to the class, and familiarizing himself with, the interesting phenomena exhibited by the invasion of the Miocene rocks by a mass of granite as described and illustrated in the book. Much to the astonishment of the class in field geology, no evidence of the intrusion of the granite could be found. On the contrary, beautifully clear cliff sections were observed showing the sandstones and shales resting upon the worn and eroded surface of the granite. An important lesson was learned as to the difference between the "*geological record*" and *recorded geology*. In the same section of our guidebook very interesting metamorphic rocks were described as occurring near Pescadero ranch house, and the class was conducted thither expectantly. Again were we astonished to find nothing whatever to warrant the state-

ments in the book, the supposed metamorphic rocks proving to be laminated volcanic flows. With so much misconception of the local geology in so authoritative a book, it seemed desirable, since the exposures were excellent, to look a little further into the geology of the shores of the bay, to ascertain from personal observation what the facts were. This was done during a second visit to the locality; and subsequently the continuation of the investigation was suggested to Mr. Posada as a suitable subject for a thesis for graduation in the College of Mining; and later both he and the writer made two extended visits to the district. The present paper embodies the results of our joint observations. It does not profess to be an exhaustive treatment of the subject, but simply to be a fuller account of the geology of Carmelo Bay than has hitherto appeared. It will take advantage of the observations of earlier writers, and will serve not only to add to our knowledge of the geology of the coast but also to correct some very misleading errors which have become current, especially regarding the age of the granite and the alleged metamorphism of the Miocene.

Besides the notice given by Whitney, which has been referred to above, brief notes may be found in the writings of the earlier geologists, Trask* and Blake,† as well as in the more recent publications of Becker.‡

PHYSIOGRAPHY AND RELIEF.

Carmelo Bay is a small indentation of the coast, situated about five miles south of Monterey Bay. It lies within two granite headlands, Pescadero Point on the north and Carmelo Point on the south,

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*Report on the Geology of the Coast Mountains, etc , by John B. Trask, *Assembly Journal*, fifth session of the Legislature of the State of California, 1854, appendix doc. No. 9, pp. 21, 22, 36. *Id.* Sixth session, 1855, appendix doc. 14, p. 28.

† Reports of explorations and surveys for a railroad from the Mississippi River to the Pacific Ocean, Vol. V House of Rep., 33d Congress, 2d Session, ex. doc. No. 91, Geol. Report, by W. P. Blake, pp. 80–82, Washington, 1856. Observations on the Physical Geography of the Mountain Ranges of California adjoining the Coast, by W. P. Blake, in the Report of the Superintendent of the Coast Survey for the year 1855, pp. 392, 393.

‡ Notes on the Stratigraphy of California, Bulletin U. S. G. S. No. 19, p. 8. Quicksilver Deposits of the Pacific Slope. Monograph U. S. G. S. No. XIII, p. 185.

the summits of these headlands being respectively 140 feet and 240 feet above the tide. The greatest length from north to south is a little less than $3\frac{1}{2}$ miles; its greatest width from the mouth of Carmelo River to a line connecting the headlands is about a mile and one-half.

There are several physiographic features of much interest. The high and prominent ridge of the Santa Lucia Range terminates abruptly on the shores of the bay.

The Carmelo River, a small stream draining the valley behind this ridge, flows into the bay from the southeast. The river is at base-level, at least in its lowest stretches, and flows through a flat flood plain about three-fifths of a mile wide. It emerges upon the bay through a rocky gate about one-eighth of a mile wide.

Both the coastal slopes of the bay and the sides of the Carmelo Valley are terraced up to elevations of several hundred feet. There is no evidence in the soundings recorded on the Coast Survey chart of a pronounced submarine delta at the immediate mouth of the stream.

The soundings plotted on the chart demonstrate the existence of a deep submarine valley which runs in from the Pacific into the southeast corner of the bay, there being 135 fathoms of water within three-fifths of a mile of the shore.

Less than a mile to the south of Carmelo River San Jose Creek enters the bay from the mountains to the southeast, through a very narrow and sharply cut V-shaped trench. This stream has not yet reached its base-level and is actively cutting.

The northern extremity of the main ridge of the Santa Lucia Range is a bold mass of granite ranging from 2,000 to 3,000 feet in elevation and sharply scored by deep ravines.

To the north of San Jose Creek the country is occupied by soft sedimentary formations, and has a much lower altitude, the summits being about 800 to 1,000 feet high, and the surface of the hills takes its character from the undulation of the slightly disturbed strata, greatly modified, however, by stream erosion and the terracing above referred to.

The shores of the bay present a picturesque and pleasant aspect. Rocky points with sea-cliffs and fringing stacks separate beautiful

stretches of white sandy beach. There are excellent examples of wave erosion in the numerous coves and clefts near Carmelo Point, and in the sub-aqueous shelf which runs out from the base of the cliffs.

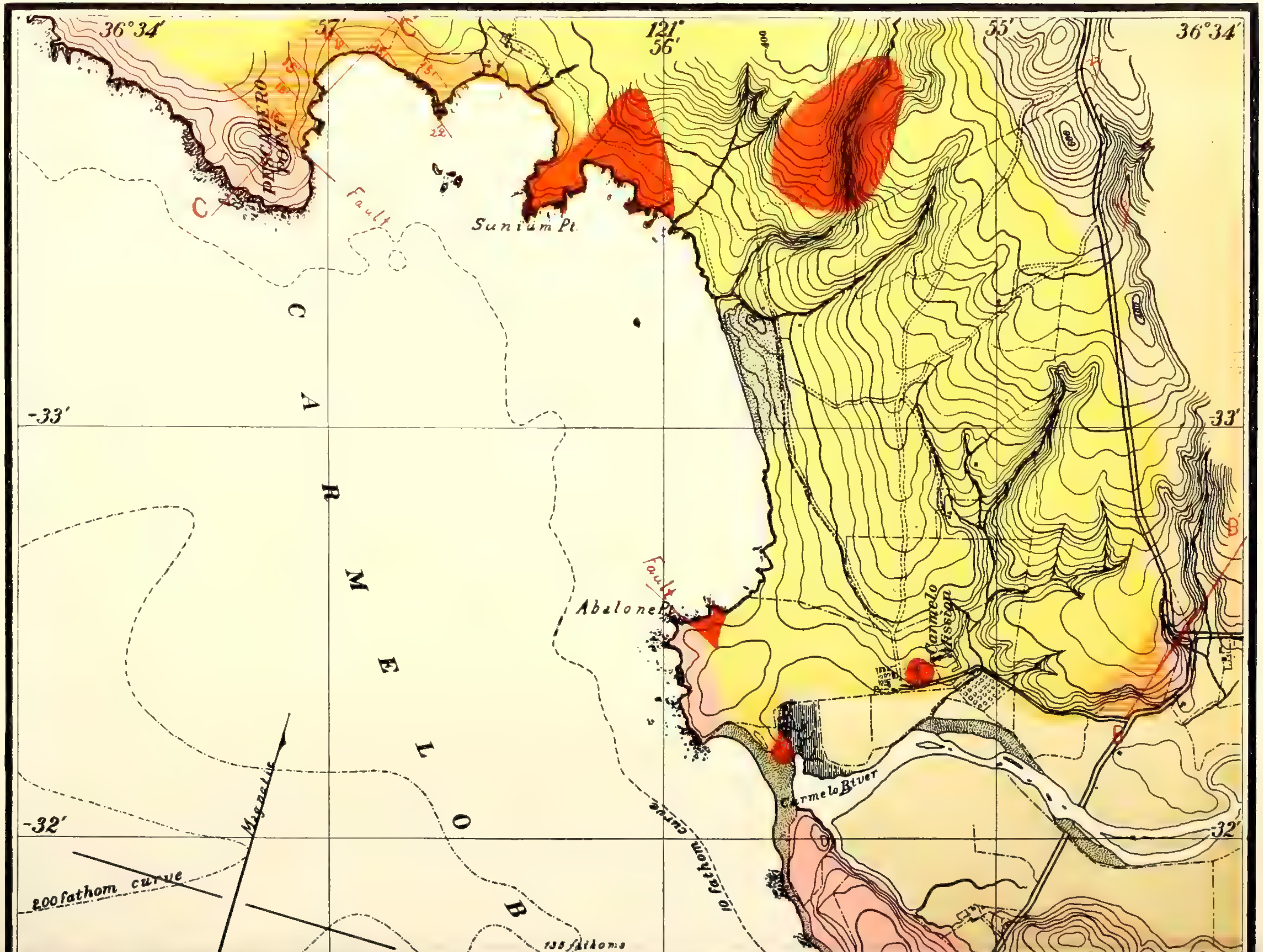
The water deepens more rapidly off shore in the southern part of the bay than in the northern.

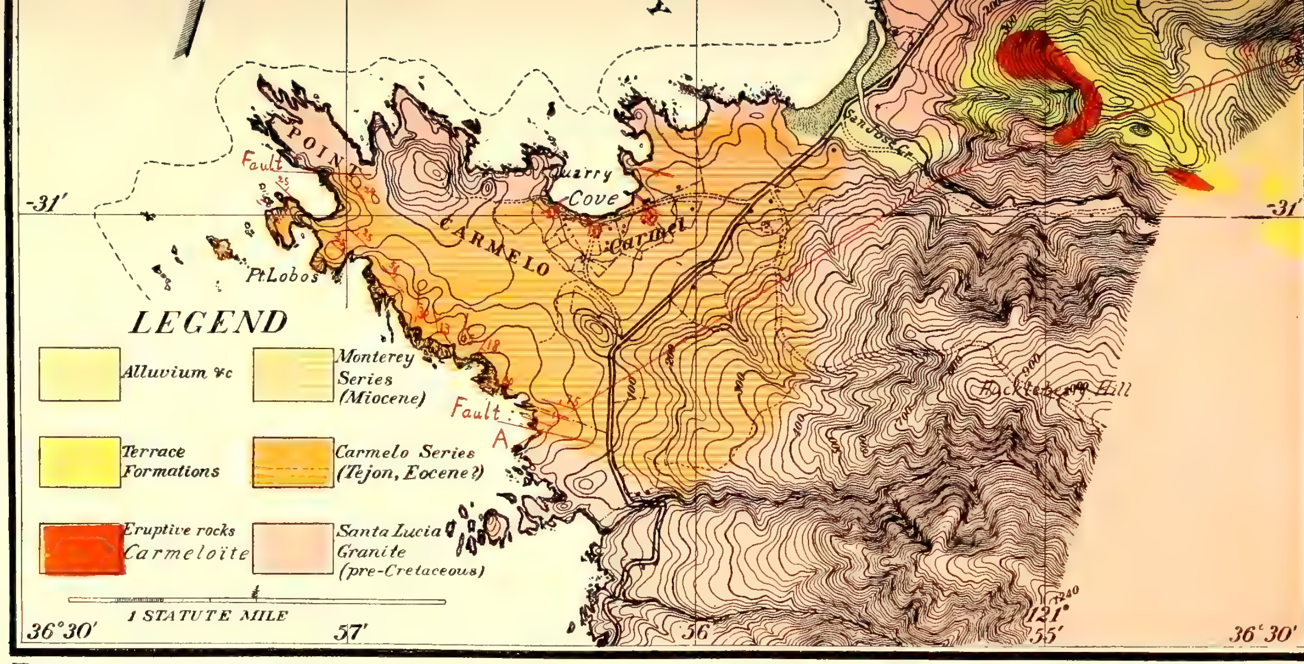
GENERAL STATEMENT OF THE GEOLOGY.

The eroded surface of a granite mass forms the basement upon which rest the sedimentary formations. On the shores of the bay this granite is the most prominent rock and excellent exposures are afforded which permit its petrographical character and its relations to the other formations of the locality to be described with precision. The rock has prevailingly a coarsely porphyritic facies, the phenocrysts of orthoclase ranging commonly from one inch to three inches in length. This granite, in the vicinity of Carmelo Bay, is in easily traceable continuity with the extensive granite mass which forms the main ridge of the Santa Lucia Range to the southward. It will therefore be referred to in this paper as the "*Santa Lucia granite*." The Santa Lucia granite is traversed, not only at Carmelo Bay but elsewhere in the range, by small dykes of a finer-grained generally feebly porphyritic granite and also by small dykes of coarse pegmatite. These dykes had traversed the Santa Lucia granite prior to the erosion which truncated the mass and prepared the surface upon which the sedimentary rocks now rest.

Reposing upon the worn surface of this granite is a series of sandstones and conglomerates, with some argillaceous shales. This series has a thickness of several hundred feet. Locally it has been much disturbed and sharply folded into vertical attitudes, and has been sunk down bodily into the granite, it being apparent that the relief from strain which was effected in the sandstone by folding, was effected in the underlying granite by faulting and shearing. This series has yielded no fossils at Carmelo Bay, but it appears to be identical with the coal-bearing sandstones of Malpaso Cañon, about two miles distant. The latter are believed, from the occurrence in them of heavy beds of fairly good coal* and from such fragments

*Turner in his admirable paper on the Geology of Mount Diablo states that

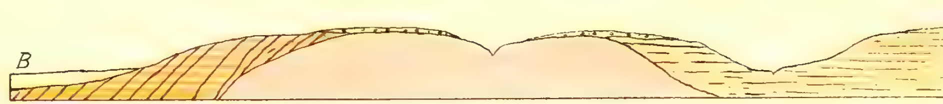

36°34′
57′
121°
56′
55′
36°34′
PESCADERO POINT
Fault
Sunium Pt.
C A R M E L O B
-33′
-32′
Fault
Abalone Pt.
Carmelo Mission
Carmelo River
10 fathom curve
200 fathom curve
Magnetic
135 fathoms



Topography reduced from U.S. Coast & Geodetic Survey Chart

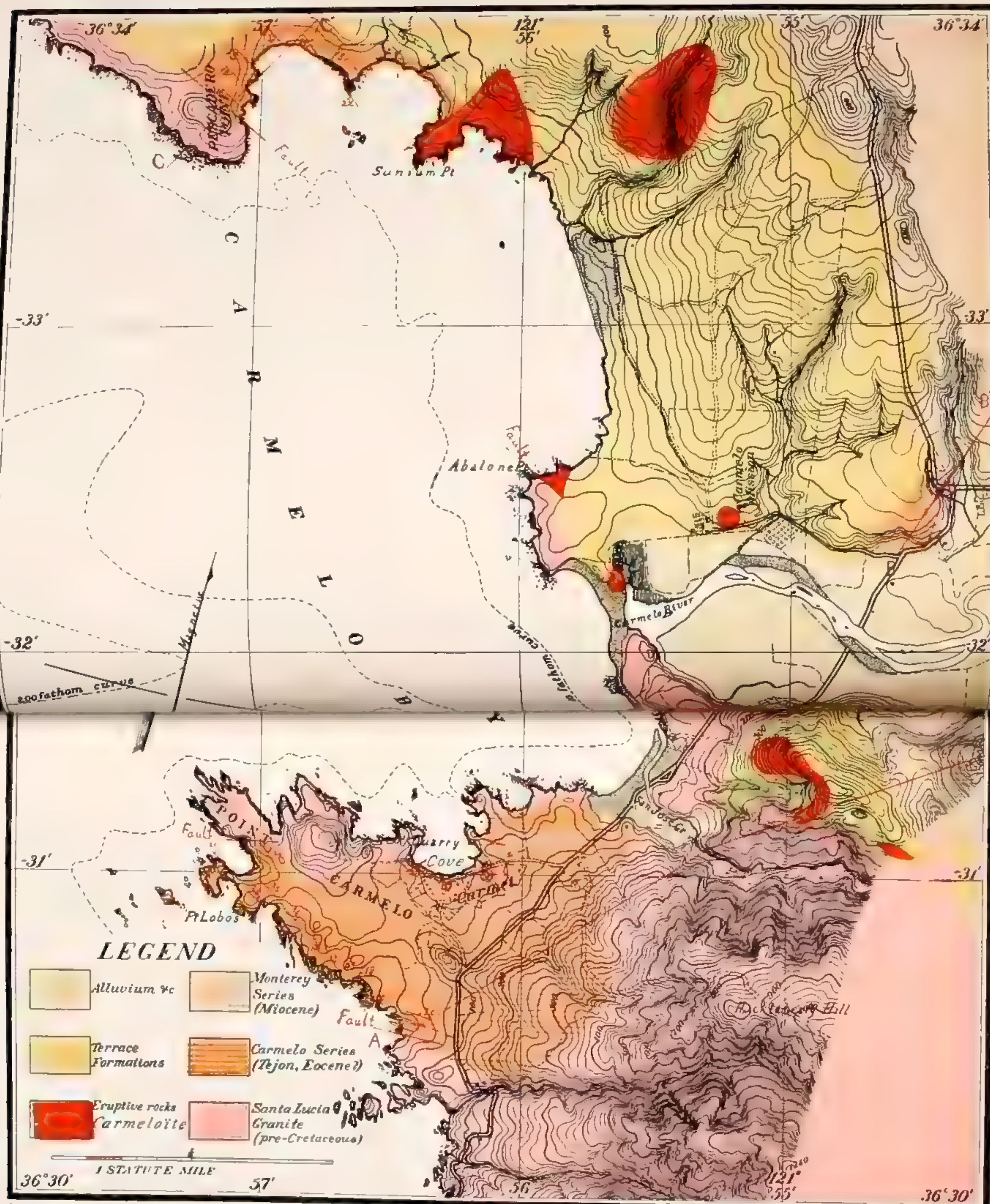
GEOLOGICAL MAP OF CARMELO BAY

Scale, horizontal and vertical, $\frac{1}{18,000}$



Scale, horizontal, $\frac{1}{7\,200}$ vertical, $\frac{1}{5,400}$

Scale, horizontal, $\frac{1}{18,000}$, vertical $\frac{1}{10,800}$.



Topography reduced from U.S. Coast & Geodetic Survey Chart

GEOLOGICAL MAP OF CARMELO BAY

Scale, horizontal and vertical, $\frac{1}{18,000}$

Scale, horizontal, $\frac{1}{7,200}$ vertical, $\frac{1}{5,400}$

Scale, horizontal, $\frac{1}{18,000}$, vertical $\frac{1}{10,800}$.

of fossils as could be found, to be of Tejon (Eocene) age. This series of sandstones and conglomerates on Carmelo Bay is therefore entatively held to be Eocene. In order to avoid giving a positive character to this correlation and for general convenience in description, these rocks will be designated in this paper the "*Carmelo series.*"

The Carmelo series was folded and subjected to erosion before the deposition of the next higher series—the Miocene. The reasons for this statement are the very evident differences in the extent to which the two series have been disturbed, and the fact that the sandstone of the lower series has been locally removed from the granite so that the Miocene rocks rest directly upon it. The Miocene formations are abundantly developed but do not extend down to the shores of the bay. The margin of the terrane has in part retreated by reason of erosive action, and in part has been covered by later formations, so that the line of exposure is about a mile distant from the shore. The series was among the first which attracted the attention of the earlier writers, Trask* and Blake,* and it has since become famous for the "infusorial" remains which it contains, being known to collectors as the Monterey formation. This name, under the form of the "*Monterey series,*" will be adopted as the local designation of the series. It is richly fossiliferous, not only at certain horizons in diatoms and radiolaria, but also generally in calcareous forms (foraminifera) and locally in molluscan and other remains. The formations which constitute the series are mostly light colored, usually white or cream-colored or yellowish, and have a soft chalky character. There are also some calcareous and some harder, compact opaline beds. Up to the present the white or cream-colored chalky portions of the formation have been described as essentially a formation of infusorial earth. Our observations cast some doubt upon this idea and show that at best it is only partially true. The characters of the formation seem to correspond rather to a volcanic ash (modified) than to an organic deposit. And siliceous organic remains form only a very subordinate proportion of its constituents

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the coal-bearing strata of Mount Diablo and of Central California generally are of Tejon age. Bulletin G. S. A., Vol. 2, p. 392. Whitney also earlier held the same view. See Geology of California, Palæontology, Vol. II, p. xiii.

*Op. cit.

except for particular layers unusually rich in infusorial forms. This idea, if sustained, of the volcanic origin of the Monterey series is of much interest, since the series has a constant general character for several hundred miles along the coast and the rocks composing it are probably made up of the same materials.

The Monterey series is over one thousand feet thick in the district around Carmelo Bay, and the whole series has been thrown into undulatory folds, the dip not exceeding usually 10° to 20°.

Since their deposition the rocks of Monterey series have been subjected to uplift, the minimum value of which is locally not less than one thousand feet, and the Carmelo Valley, with a width on its bottom of half a mile, has been worn out to base level through them.

Within the area examined are six geographically distinct patches of volcanic rock which ~~are~~ is of peculiar mineralogical composition and for which the name *Carmeloïte* is proposed. Some specimens yield to chemical analysis results which ally them with the basalts, while others correspond rather to the andesites. These eruptive rocks, though varying much in aspect, texture, structure, and composition, are probably derived from one magma, and are of the same age. They are characterized by the presence of an interesting mineral, here named *iddingsite*, of which a detailed description is given in the sequel. The areas occupied by these rocks are separated by reason of their being mantled by later formations, and their outcrops are simply their protrusions through the overlying and newer rocks. If the latter were stripped off, the six separate patches would probably fall into three, and possibly only two, distinct areas. These eruptive rocks are certainly of later age than both the Carmelo series (Eocene) and the Monterey series (Miocene). They belong to the age of the terrace formations referred to below. They are submarine extravasations intercalated with the Pliocene (?) formations.

Imposed upon the worn slopes of the rocks of the Monterey series (Miocene) are various formations of conglomerate, sandstone, gravel, sand, and clay. As indicated by their petrographical designations these formations are in some places quite coherent and firmly cemented, while at others they are loose and incoherent. The

more compact and coherent facies resemble somewhat the rocks of the Carmelo series, from which, however, they are easily discriminated by the occurrence in them of fragments of white shale derived from the Monterey series. These formations are spread over the surface of the successive terraces which score the slopes of the hills to an altitude of many hundred feet. They will therefore be referred to in the following pages as the "*Terrace formations.*" The same designation is also used in the mapping to cover a terraced delta of the San Jose, which is thought to be of Pliocene age. It is the newer of these formations which cover the eruptive rocks and partially obscure their relations to the older rocks. With the terrace formations are associated numerous Pholas borings in the rocks behind the terraces.

The only other formations which call for mention are the alluvial flood plain of the Carmelo River and the blown sand near the shore. These formations will not be further noticed.

THE SANTA LUCIA GRANITE.

Petrography.—The Santa Lucia granite is a coarse-grained gray rock with huge phenocrysts of orthoclase. The coarse granular ground-mass of the rock consists essentially of vitreous quartz, whitish or greenish white feldspar,and an abundance of black, lustrous biotite. The quartz is the most largely developed mineral in the ground-mass, there being areas of it as much as two centimeters in diameter. The feldspar is less largely developed and the biotite ranges in size from one to two millimeters. Striations may be occasionally detected on the basal sections of the feldspar in the ground-mass, showing that some of it is plagioclase.

The phenocrysts are the most striking feature of the rock. These consist of immense crystals of glassy orthoclase, usually elongated in the direction of the clino-axis. They are very commonly, but not always, twinned on the Carlsbad law. These phenocrysts not infrequently attain a length of ten centimeters, and from four to five centimeters is a very common size. These elongated crystals may be seen at favorable exposures, as in the quarry at Carmelo Cove, to have sometimes a very pronounced parallelism in their orientation in the ground-mass. Fig. 1 is a diagramatic

sketch of a slab in the quarry showing this parallelism or stream-like distribution of the orthoclase phenocrysts in the ground-mass. The appearance is very suggestive of a flow structure in a viscous mass slowly crystallizing.

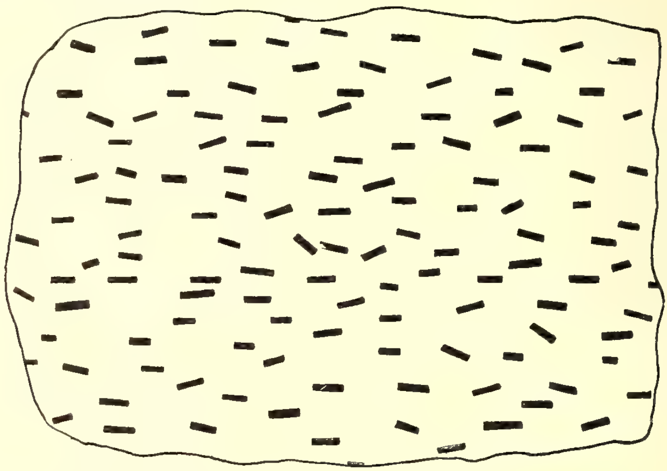

Figure i.—Diagram to illustrate the parallelism of the orthoclase phenocrysts in the Santa Lucia granite, at the old granite quarry, Carmelo Cove.

The basal cleavages of the phenocrysts are very lustrous, but they all show in a marked degree the appearance known as "luster mottling," due to the inclusions of foreign minerals in the crystals. These inclusions were found on microscopic investigation to comprise crystals of plagioclase, orthoclase, quartz, biotite, and muscovite. The first four of these are very abundantly represented. The muscovite is more sparing. In some cases these inclusions are so abundant as to constitute, on an estimate, as much as 20 per cent. of the phenocryst. With the exception possibly of the micas, these inclusions are arranged in definite planes and lie parallel to either the clinopinacoid or to the prism faces. While the phenocryst host is usually quite fresh and glassy, the included feldspars are frequently cloudy, owing to partial decomposition, and the regular arrangement of these cloudy inclusions gives the large orthoclases a distinct zonal appearance. The inclusions are in the sections examined very commonly about .25 to 1 mm. in length, while

some attained a size of 1.5 mm., and one was found to be as much as 3 mm. in greatest length. Of these inclusions the feldspars usually present sharply idiomorphic forms, and are frequently twinned. The quartzes occur prevailingly in rounded bleb-like crystals, sometimes angular, and recall the rounded quartzes of the quartz-porphyries. The biotite has the form of thick little plates, which show sometimes hexagonal sections. The muscovite occurs in ragged, shred-like patches. Minute slender needles, probably apatite, also occur in the phenocrysts, but these are scattered in all directions and do not appear to have any definite relation, as to their orientation. to their host.

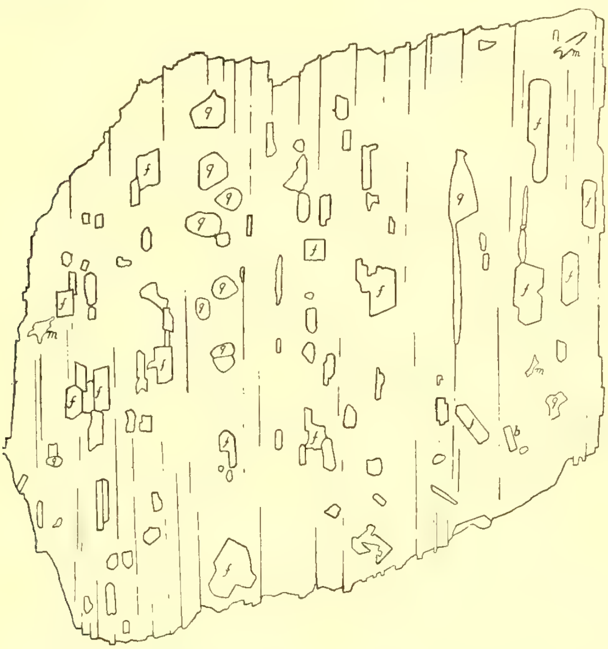

FIGURE 2.—Section of orthoclase phenocryst of Santa Lucia granite, parallel to basal pinacoid (001), showing inclusions of quartz, *q;* feldspar, *f;* biotite, *b;* and muscovite, *m.* All the quartzes have a common orientation, with the optic axis perpendicular to the basal pinacoid of the host; and the feldspars have a common orientation by groups. × 8.

The orientation of the quartzes and feldspars is very remarkable. Not only are these minerals distributed in their host in definite

planes but each mineral has a common orientation for distinctly isolated individuals widely scattered through their host. Thus, for a considerable area, all the plagioclase crystals which lie in the plane of the clinopinacoid have a common orientation, extinguishing light simultaneously throughout the area, embracing perhaps a score or more of individual crystals, all sharply idiomorphic. What this orientation is with reference to the crystallographic orientation of the host has not yet been definitely determined. A similar community of orientation may be observed in the plagioclases lying parallel to the prism faces.

In the case of quartz, also, not only was this community of orientation established, but the relation of the common orientation to that of the host was ascertained. The law appears to be that *the vertical axis of the quartz is perpendicular, or very nearly perpendicular, to the basal plane of the orthoclase.* Thus in Fig. 2 all the quartzes (*q*) show a uniaxial interference figure, which is only very slightly eccentric to the axis of vision. The eccentricity is constant for all the quartz individuals, and is believed to be due to the slight obliquity of the section to the basal plane of the feldspar. Sections were examined from two other localities, and the same law was found to hold.

The uniform orientation of quartz in isolated masses intergrown with feldspar is a well-known feature of pegmatitic and granophyric rocks, but the definite relation between the orientation of the quartz and that of the orthoclase, which is here described, has not, so far as the writer is aware, been hitherto observed. The community of orientation of idiomorphic plagioclases inclosed in orthoclase is also apparently a novel and certainly very interesting fact. *The orthoclase seems to have exercised a very large control upon the distribution and orientation of the separate and distinct individuals of both quartz and feldspar which are inclosed in it.* From what has been said of these inclusions, it is clear that we have to deal neither with "Schillerization" products, nor with the ordinary minute original "interpositions," which are common in the feldspathic constituents of igneous rocks, nor with the poikilitic structure of Williams. All the minerals of the ground-mass occur as inclusions in the phenocrysts, not as minute microlites, but as comparatively large crystals. And the relations of these inclusions to the phenocrysts on the one hand,

and to the ground-mass of the rock on the other, seem to afford some very suggestive and forcible evidence as to the progress of crystallization in the magma which yielded this granite. We cannot regard the large orthoclase phenocrysts, so perfectly developed crystallographically, as the first products of consolidation, which floated about freely in the magma till surrounded by the later consolidation, in granular form, of the ground-mass. For these orthoclases are full of crystals which are themselves of the nature of phenocrysts, and which are certainly not of later generation than their hosts. Nor can we regard these inclusions as representative of the first generation of crystals which were subsequently caught up and inclosed by the crystals of a second generation—the orthoclases, for, as we have seen, the orthoclase exercised a very powerful control over the distribution and orientation of the inclusions, and this can only be assumed to have been effective during the growth of the latter. The minute idiomorphic crystals so abundant in the phenocrysts are, moreover, not observable in the ground-mass, as they probably would be if they had been the products of the first generation, and owed their inclusion in the orthoclases to their prior free existence in the magma. Thus it appears that these interesting and remarkable inclusions of feldspar and quartz are neither anterior nor posterior to their hosts in generation, but are of simultaneous development. Such a statement cannot at present be made with reference to the inclusions of mica and apatite.

One other interesting circumstance remains to be noted. The perfection of form of the large phenocrysts of orthoclase has been alluded to. This implies, of course, a sharp demarkation between the bounding planes of the phenocrysts and the ground-mass in which they are imbedded. When the rock has undergone secular decay, the phenocrysts may be picked from the ground-mass in fresh condition and good form. While the phenocrysts have these true crystallographic faces as bounding planes, and are thus sharply marked off from the ground-mass, there is no corresponding sharp demarkation between the *inclusions* of the phenocrysts and the ground-mass of the rock. And for this reason the surfaces of the phenocrysts, removed from the decayed rock, are always rough, owing to the protrusion beyond the boundary planes of the included

minerals. That is to say, there appears in each case to have arrived a stage in the progress of crystallization of the magma at which the growth of the phenocrysts ceased, while the inclusions, which were being simultaneously formed, continued to separate, and continued out as the ground-mass of the rock, so that on the periphery of the phenocrysts it is difficult to say whether the crystals of feldspar, quartz, and mica, which are partly imbedded in the phenocryst and partly protrude beyond its surface, are to be called inclusions, or ground-mass. The continuity of growth of the inclusions of the phenocrysts into the ground-mass seems to be unquestionable. But with the arrested growth of the phenocrysts two changes took place in the crystallization of the material which yielded both inclusions and ground-mass: (1) It ceased to assume idiomorphic forms, and developed immediately an allotriomorphic granular structure. (2) The size of the constituent minerals of this allotriomorphic granular ground-mass became very much larger than the idiomorphic forms deposited as contemporaneous inclusions in the phenocrysts.

It is difficult to say whether the inclusions are, as a rule, more abundant toward the periphery of the phenocrysts than in their central parts, but in some cases this seems to be so, especially as regards the biotite. The phenocrysts are comparatively free from ordinary minute interpositions and liquid inclusions.

With regard to the ground-mass a word or two remains to be added to what has already been said. There is apparently as much plagioclase as orthoclase in this portion of the rock; perhaps there is an excess of plagioclase, the latter proportion being indicated, also, by the analyses of the rock given below. The plagioclase is probably oligoclase for the most part. Microlites of apatite may frequently be observed, and minute interpositions and liquid inclusions are not uncommon in both feldspar and quartz.

Muscovite is practically absent from the ground-mass, although an occasional plate may be here and there detected, and the rock would ordinarily be classed as a porphyritic granitite. The preponderance of soda and lime in the bulk composition of the rock, together with the corresponding abundance of plagioclase in its mineralogical composition indicate its affinity with the quartz-

diorites. The ground-mass of the rock certainly belongs to that intermediate type for which Becker has recently proposed the term *granodiorite*.* Pyrite is occasionally present.

A feature of interest connected with the physical character of the ground-mass is the abundance of minute cracks which traverse it in all directions. These cracks may be readily observed with the aid of a lens. They cause the rock to be rather friable and easily susceptible to disintegration. It is very difficult on their account to make satisfactory slides of the ground-mass. These cracks do not appear to obey any definite law of direction, and may, perhaps, be ascribed to the presence of the large phenocrysts, and the unequal and intermittent tension set up by their differential expansion and contraction in different crystallographic directions. It is, however, known that the rock has been subjected to very considerable mechanical stresses of an orogenic character since the deposition upon it of newer formations, and the possibility of the irregular fissuring being due to these strains must be considered. If the latter were the cause, we would expect to find definite systems of shearing and faulting, and the phenocrysts should also be affected. The phenocrysts are, practically, unaffected by these cracks, so far as has been observed. The ready disintegration induced by these fissures, together with the occasional occurrence of pyrite in the rock, are probably the causes which have led to the abandonment of the quarry as a source of building material.

The following is an analysis of the rock from material selected so as to represent as nearly as possible the composition of the granite as a whole, a selection requiring some judgment on account of the large size of the phenocrysts:

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*Geological Atlas of the U. S., Sacramento sheet. Glossary of rock names.

Analysis of Granite from Quarry at Carmelo Cove.

$Si\,O_2$	71.63
$Ti\,O_2$	trace
$Al_2\,O_3$	13.86
$Fe_2\,O_3$	0.46
$Fe\,O$	2.76
$Ca\,O$	3.26
$Mg\,O$	trace
$K_2\,O$	2.65
$Na_2\,O$	3.40
$P_2\,O_5$	0.20
Ignition	.89
	99.11
Sp. g.	2.68

Later Granite Dykes.—The dykes of later granite which intersect the Santa Lucia mass vary in size from an inch, or a few inches, to several feet in width. The smaller dykes, less than a foot in width, are more common than the larger ones. They appear to have no prevalent trend but traverse the older mass in all directions. They are inclined at all angles to the horizon. They are not so abundant in the immediate vicinity of Carmelo Bay as they are a little to the southward.

The rock of these dykes is much finer grained than the Santa Lucia granite. It is commonly not appreciably porphyritic, and in those dykes where phenocrysts of orthoclase appear the latter are of small size. The rock is much more compact or less friable than the Santa Lucia rock, and does not appear to be affected by the irregular minute cracks which traverse the latter. Since the disturbances which have affected the Santa Lucia mass are of later age than the dykes, the suggestion that the cracks in the former are due to the presence of the large phenocrysts, rather than to orogenic movements, is strengthened. The dyke rock is characterized by a paucity of mica, and this is so pronounced locally that it may properly be regarded as an aplite. It is either gray or slightly flesh tinted, and the feldspars are usually more or less kaolinized.

These dykes sometimes show very beautifully the shearing to

FIGURE I.—ILLUSTRATING THE SHEARING OF THE SANTA LUCIA GRANITE AT MALPASO CANON.

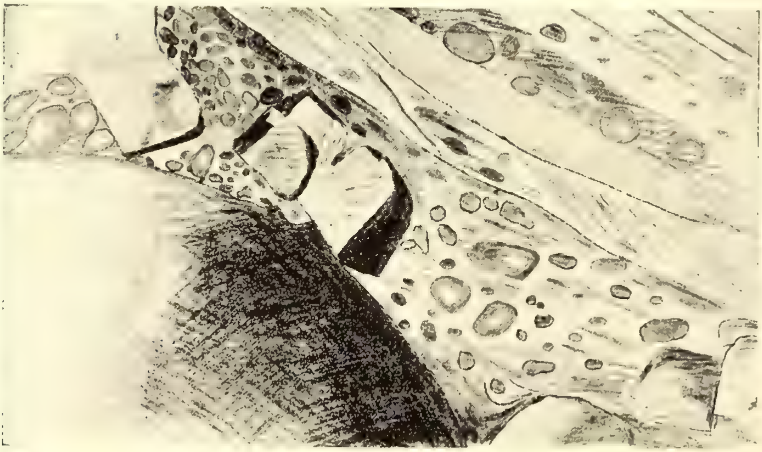

FIGURE 2.—ILLUSTRATING ROUNDED FORM OF SANTA LUCIA GRANITE UNDERLYING CONGLOMERATE OF CARMELO SERIES, CARMELO POINT.

which the Santa Lucia granite has been subjected. An instance of this is shown in the photograph of a cliff face on Malpaso Cañon, a little to the south of Carmelo Bay, which is reproduced in Plate 2, Fig. 1.

Pegmatite Dykes.—Beside the dykes of granite there are numerous narrow dykes of pegmatite which also traverse the Santa Lucia granite. These dykes are usually only a few inches in width. They consist essentially of a very coarse granular aggregate of orthoclase and quartz, with occasionally some black mica in broad plates and a few shreds of muscovite. The feldspar very commonly has a pronounced flesh tint, and is fresh and lustrous, while in other cases it is kaolinized and bleached white. In a few cases the cleavage surfaces of the feldspar show a "luster mottling" similar to that characteristic of the phenocrysts of the Santa Lucia granite; but this does not appear to be a common feature.

The age of the pegmatite dykes relatively to the granite (aplite) dykes has not been determined, as they have not been observed to intersect. Possibly both aplite and pegmatite are of synchronous formation.

Relation to Other Formations.—After the intersection of the Santa Lucia granite by dykes of granite (aplite) and pegmatite, the mass was deeply eroded. The coarsely crystalline granular character of the rock is warrant for believing that it solidified under deep-seated conditions, and that its plutonic facies has been exposed only by the removal of a large volume of superincumbent rock. The eroded surface of the granite, where it passes beneath the sedimentary rocks, is well seen in cliff sections, particularly at Carmelo Point, where a photograph of the contact was obtained, which is reproduced in Plate 3. The surface of the granite here passes beneath a basal conglomerate of the Carmelo series. The surface is smooth and fresh, and presents no evidence of important secular decay prior to the deposition of the conglomerate. The surface is much smoother than the surfaces presented by the granite where not protected by an overlying formation. The difference may perhaps be ascribed to the progress of secular decay since the deposition of the conglomerate, the tendency in a partially decayed rock being to weather rougher than in the case of a fresh rock. But

while the surface is smooth, it is not even, as may be seen in Plate 3. There are low, rounded, lumpy portions, and the surface has in places a domed aspect, as is further illustrated in Plate 2, Fig. 2.

There is thus no shadow of doubt as to the intervention of a long period of erosion between the solidification of the granite and the deposition of the conglomerates and sandstones of the Carmelo series. As these are the oldest sedimentary rocks in the district, it is certain that the granite underlies the whole of the sedimentary series as a basement, and the notions which have become current of the intrusion of the granite into the Miocene are utterly erroneous. Indeed, the direct superposition of the shales of the Monterey series (Miocene) upon the worn surface of the granite may be as indubitably observed as in the case of the Carmelo series. That the granite is anterior to the eruptive rocks is also proved (1) by the fact that bowlders of the granite have been caught up and imbedded in them, (2) by an inspection of the immediate contact of the two rocks, which may be observed at two good exposures, and (3) by their intersection of the Carmelo series, rich in bowlders of the granite. The granite is thus the oldest rock on this part of the coast, and if, as has been suggested, the Carmelo series is of Eocene age, the granite is certainly pre-Tertiary. But farther north, across the Bay of Monterey, in the Santa Cruz Range, the granite, without doubt of the same geological age as that of the Santa Lucia Range, bears a similar basal relation to rocks which are of not later age than Cretaceous. The erosion which truncated the Santa Lucia granite was, therefore, largely completed in pre-Cretaceous time, and the age of the granite is at the latest pre-Cretaceous.

THE CARMELO SERIES.

Petrography.—The rocks of the Carmelo series are prevailingly thick-bedded conglomerates of dark color, and thinly-bedded tawny sandstones. There is also a subordinate proportion of shale and shaly sandstone. The conglomerates are most abundant at the basal portion of the series, but also alternate with the sandstones throughout the entire thickness. The pebbles in the conglomerates are usually not large, averaging in the great mass of the formation from one to four inches in diameter, and in general resemble stream

Carmelo Conglomerate reposing upon worn surface of Santa Lucia Granite, Carmelo Point, South Side

detritus. There are, however, occasional larger bowlders, and locally, as to the west of Sunium Point, these are very abundant. The pebbles consist chiefly of purple and red quartz-porphyry, greenstone, granite (Santa Lucia) quartz, and highly siliceous metamorphic rocks. The conglomerate is usually hard and compact, and is remarkable for the shattered and cracked appearance of the pebbles. This cracking is, of course, secondary and subsequent to their deposition in the formation. In some cases, as on the shore to the east of Carmelo Cove, the pebbles are not only cracked, but are distinctly sheared or faulted along numerous fine, irregular fault planes. The faulting cannot usually be detected in the matrix, but can be followed from pebble to pebble, the dislocation in each not exceeding one or two millimeters as a rule. These shear planes do not vary greatly from the vertical.

Occurrence.—The rocks of the series occur in three distinct areas within the limits of our field. The largest of these is on Carmelo Point, where they occupy, as represented on the map, a small synclinal basin let down by faulting into the granite upon which they rest. The attitude of the beds varies from vertical to nearly horizontal, and the general structure of the basin is that of a complex syncline, the rocks in a general way dipping from the rim towards the center. Usually the strike and dip vary so rapidly that it is not an easy matter to find a section suitable for a measurement of the thickness of the series. On the south side of the extremity of Carmelo Point, however, the strike is fairly constant for several hundred yards, and the dip varies from 20° to 26°, so that a favorable section is afforded upon which to measure the thickness. The estimate arrived at was 800 feet for the minimum thickness of the series.

As has already been stated, the relation of the Carmelo series to the Santa Lucia granite is that of a sedimentary deposit reposing upon a worn and uneven surface. The superposition is well seen on the south side of the Carmelo Point, and is represented in Plate 2, Fig. 2, and in Plate 3.

In so shallow a basin of such limited extent, with sandstones resting on a great mass of granite in undulating folds, or in vertical attitudes, it becomes a matter of much interest to ascertain how the

underlying granite was affected by the movements which folded the sedimentary rock. The structure of the latter in bedded sheets permits of a folding which is not possible in the granite without intense crushing throughout the mass. In the absence of this crushing it would appear, *a priori*, that the stress which affected the granite during the folding of the superincumbent strata could only have been relieved by faulting and shearing. The observed facts also warrant this belief. At the contact of the sandstone and granite it is evident at several places that faulting has occurred, and the shearing to which the granite has been subjected is well exhibited at Malpaso Cañon, as illustrated in Plate 2, Fig. 1.

The second area of the Carmelo series in order of importance is at the north end of Carmelo Bay, and is well and continuously exposed between Sunium and Pescadero Points. The rocks here are the same tawny thin-bedded sandstones and heavy-bedded conglomerates. In the eastern portion of the section the structure is not very apparent, owing to the coarseness of the conglomerates and the thickness of the beds. The formation is here seemingly flat, or but gently undulating. To the westward of the little creek which enters the bay at the Chinese village, however, the structure becomes clearly recognizable and is of a very definite character. The strike of the rocks from here to Pescadero Point is uniformly northwest and southeast and the dip is constantly southwest at angles which range from 15° to 22°, but on the average do not much exceed 15°. The strata having this attitude may be followed across the strike without a break to the granite of Pescadero Point, towards which they dip. Here at a small cove on the east side of the point they abut squarely on the granite, having been let down against it by a sharp fault. The trend of this fault is apparently the same as the strike of the rocks. The section affords an excellent opportunity for obtaining a minimum value for the thickness of the series, and also for measuring approximately the amount of the downthrow on the fault. Estimates based on careful plotting give a value for the thickness of 725 feet, a figure which agrees very well with that obtained from the section on the south side of Carmelo Point. The amount of the downthrow is at least 850 feet. The relations are shown in the profile section C-C′, Plate 1.

The easterly limit of these sandstones and conglomerates is not less interesting than that at Pescadero Point. Here on the northwest side of Sunium Point the conglomerates are in sharply-defined contact with the Sunium Point mass of carmeloïte. The plane of contact is vertical, or nearly so, and the eruptive character of the massive rock is very evident, there being considerable masses of the conglomerate inclosed in it in the immediate vicinity of the junction of the two formations. Back from the shore of the bay the strata are covered by the terrace formations for the most part, and by soil, so that the extent of the area occupied by these rocks to the northward cannot be mapped with the same precision as in the case of the basin on Carmelo Point. The series here, however, probably occupies a similarly limited structural trough or basin, since the underlying granite is well exposed all the way around the coast from Pescadero Point to the town of Monterey, and the only direction in which it might extend is to the eastward beneath the shales of the Monterey series; and in this direction occur masses of eruptive rocks.

The third occurrence of the Carmelo series within the area under examination is at the junction of the main coast road with the short branch road which leads westerly to the Mission church. Here we have the same alternation of sandstones and conglomerates exposed in a cutting of the road for several hundred feet. The strata are reposing upon a projecting knob of the Santa Lucia granite. The rocks are dipping away from the granite westerly at angles which vary from 20° to 47°, and show evidence of differential movement near the contact, due to the disturbance which caused them to assume such steep attitudes. They could only have assumed this steep dip away from the granite by a relative shearing along the contact of the massive and the bedded terranes. The relation of the sandstone and conglomerates to the granite is illustrated in section B-B′, Plate 1. The pebbles of the conglomerates here exhibit the same cracked appearance as at Carmelo Point, though to a much less marked degree.

Correlation.—No fossils have been found as yet in the rocks of this series; and in view of the unconformable relation of the series to the rocks both above and below, its precise correlation must for

the present be very largely a matter of conjecture. The only clew we have as to the age of the rocks is their probable identity with similar sandstones in Malpaso Cañon which have intercalated with them considerable beds of coal, and which are therefore probably of Tejon (Eocene) age. The Malpaso Cañon coal basin is also quite similar structurally to the basin on Carmelo Point, being sharply folded into a synclinal funnel, and let down by shearing and faulting into the granite upon which it rests. Mr. Turner's opinion as to the Tejon age of the coal-bearing formations of Central California has already been quoted *supra.*

THE MONTEREY SERIES.

Petrography.—The rocks of the Monterey series, as displayed in the vicinity of Carmelo Bay, are representative of the Miocene whereever it occurs for several hundred miles along the coast of California. They are prevailingly white or light yellowish strata of a shaly character. They are soft and chalky and may usually be scratched with the finger nail. Notwithstanding their soft character, they are peculiarly resistant to weathering action, and yield little or no sedentary soil. This is due to their insolubility in meteoric waters. The rock never presents any evidence whatever of decomposition or secular decay, and wherever the rocks are exposed in road cuttings, etc., the broken edges of the shale lose little or none of their sharpness. The strata are traversed by numerous irregular jointages, which induce a mechanical disintegration into sharp blocks. The shale has very commonly a peculiar porous structure which may be seen with the unaided eye, but better with a lens. The pores are rounded or oval in sections afforded by the broken surface of the shale. They are arranged in layers in the bedding planes. They never anastomose, but always have a distinct individuality. Their appearance suggests the removal by leaching of some soluble material which once occupied the pores. This idea is sustained by a more critical examination of them with a good lens. Such an examination reveals the fact that in very many cases the pores are the hollow mouldsof minute univalve shells. As the character of the pores is thus indubitable for a great many, it is a fair inference that the whole of the porous structure of the rock is due to the leaching

out of small calcareous shells—apparently foraminifera, an that the formations of this series must have once teemed with such remains. Besides the moulds of these minute shells there are in various parts of the formation also numerous casts of Miocene molluscs.

Occasionally there may be detected in this shale a few irregular specks of bitumen, and the occurrence of economically important deposits of this substance in the same formation, in other parts of the coast, has given rise to the term "*bituminous slate*," which has sometimes been used as a designation for these rocks. Almost any specimen of the shale, however white it may appear, will yield a distinct bituminous odor when heated in a closed tube, turning black and then bleaching white. Besides these prevailingly chalky white formations, which probably constitute over 95 per cent. of the entire volume of the series, there are some other facies of the same formation, and a very subordinate proportion of other rocks. The shale may, at a few points on the main coast road, be observed to be to a very limited extent silicified and take on the appearance of silicified wood. The silica is apparently chalcedonic, and has replaced the shale without obliterating the shaly layers, though quite frequently veins of the chalcedony cut the latter transversely.

Apart from these local and secondary silicifications there are thin beds of a dense, compact, light gray, opal-like rock. These contain, like the chalky shale, numerous hollow moulds of minute univalves and occasional impressions of a bivalve of the genus macoma. The pores formed by these moulds in the opaline rock are not so numerous as in the chalky facies; they are also more sporadic and are not arranged in bedding planes.

The rock is entirely unaffected by boiling in hydrochloric acid, has a conchoidal fracture, yields water in the closed tube, and may be scratched with a knife like opal. The tongue adheres strongly to the broken surface of the rock. Fragments of this opaline rock, or, indeed, of any portion of the shaly series, whether chalky or opaline, turn black when heated on a piece of platinum foil and then on continued heating burn white again. This, together with the bituminous odor yielded in the closed tube, indicates the presence of a carbon compound distributed through the rock, and is suggestive of the source of the asphaltum which is elsewhere found in

heavy deposits in these rocks. The density of the rock is 2.018. The ultimate source of the carbon compound, the presence of which is revealed by these simple tests, was doubtless the bodies of the minute animals whose shells have been removed by leaching.

The fact that the moulds of the minute univalves are very sharply defined and quite empty of mineral matter, indicates that these opaline beds are original formations and not secondary silicifications. There are gradations from the distinctly opaline varieties to the chalky. Near the base of the series at the town of Monterey, there are some sandstones. There are also occasional lenses of a dense yellowish to mauve-colored fossiliferous limestone, and in the first ravine east of the main coast road on the north side of the Carmelo River, there are some beds which are both calcareous and gritty. These beds are usually more or less of a rusty yellow color and they are usually fossiliferous. Certain beds, also, in the vicinity of Monterey are so rich in minute siliceous organisms that they have been described frequently as beds of infusorial earth.

Origin of the White Shale.—The white shale of the Monterey series is certainly a very remarkable and unique sedimentary formation. It is certainly over 1,000 feet in thickness at Carmelo Bay, richly fossiliferous, and is neither a sandstone, a limestone, nor an argillite except as regards a very small percentage of the total volume. Infusorial remains are abundant in certain portions of the series, and their discovery, taken together with the soft chalky character of the formation, has led to the belief entertained by earlier observers that the entire series is of organic origin, and is made up of the siliceous remains of diatoms, radiolaria, sponges, etc., etc. Such a conception of the origin of the series, taken with its great thickness, would of course imply an enormous time for its accumulation. This conception is, however, probably only partially true, as our studies have shown. A microscopic examination of a large number of specimens taken from many different localities reveals the fact that the rock usually contains no microscopic organic remains other than those which are calcareous and which dissolve with brisk effervescence in very dilute acid on the stage of the microscope. Even these calcareous forms are very scarce, having for the most part been leached out as above indicated, and so giving rise to a porous struc-

ture. The infusorial beds at Monterey appear, therefore, to be exceptional and not representative of the series as a whole.

Moreover, it becomes probable from a microscopic examination that the mass of the white chalky shale, in part at least, is the fine ash of a very acid volcanic eruption. The bulk of the rock is a finely granular, seemingly homogeneous, cloudy, isotropic substance, which in some cases shows an irregular, angular, reticulated aspect, as if composed of fragments of glass cemented by an isotropic paste. Through this, as a ground-mass, are scattered broken (never water worn) crystals of quartz, orthoclase, plagioclase, and biotite, together with a small proportion of fragments of hornblende. There are also some minute crystal fragments of indeterminate minerals. In some cases there may be observed a little secondary chalcedony. The opaline beds differ microscopically from the prevalent chalky rock only in that the ground-mass is less granular in aspect. The fragments of crystals of quartz, feldspar, etc., which are scattered through it are fewer in number than in the chalky rock. The suggestion of the volcanic origin of the shale of the Monterey series yielded by the microscope is strengthened by a chemical analysis of a representative specimen of the chalky rock. The results of the analysis are as follows:—

$Si\,O_2$	86.89
$Al_2\,O_3$	2.32
$Fe_2\,O_3$	1.28
$Ca\,O$	0.43
$Mg\,O$	trace
$K_2\,O$	1.26
$Na_2\,O$	2.32
Ignition	4.89
Total	99.39

The specific gravity varies from 1.8 to 2.1, a result which is probably too low on account of the porous character of the rock, and the consequent retention of air in its interior portions.

The character of the ground-mass of the shale and of the opaline beds also renders its determination as of volcanic or of organic origin difficult. It is a homogeneous but granular and cloudy iso-

tropic substance, which can, on the whole, only be regarded as an amorphous form of silica. Such silica can, farther, it seems to us, only be regarded as of the nature of an original chemical deposit. The question is whether the silica was derived from organic remains or from volcanic glass. Whichever form the silica had originally, there seems no escape from the conclusion that the sea water has affected it on a wholesale scale as a chemical reagent, dissolving it and reprecipitating it as pulverent or gelatinous silica. The chalky formations probably represent the pulverent deposit and the opaline beds the gelatinous. Are there any criteria for distinguishing whether this homogeneous isotropic ground-mass is derived from volcanic glass dissolved in sea water, or from organic remains affected in the same way? So far as we can discover, there are no direct criteria available. There are, however, indirect considerations which, though not demonstrative, are weighty, and favor the volcanic hypothesis. These may be thus summarized:—

1. Siliceous organic remains are not common throughout the great mass of the formation. Calcareous organisms were very abundant, but are now for the most part leached out, leaving definite cavities or moulds. Siliceous organisms, like those of the Monterey infusorial beds, appear to be limited to certain definite horizons of small vertical extent. No siliceous organisms have been found in our examination of the shale near Carmelo Bay.

2. The chemical analysis corresponds approximately to that of a very acid soda rhyolite, and not to that of an organic deposit.

3. The angular fragments of mineral scattered through the ground-mass are those of an acid volcanic rock, and they are not water worn.

If this hypothesis of the volcanic origin of the Monterey series should stand the test of future research, our current ideas regarding the Miocene of the California coast would have to undergo an important modification. Instead of being an organic deposit of excessively slow growth, we should have to regard it as an ash of comparatively rapid accumulation, with calcareous organic remains far exceeding the siliceous.

Although the volcanic hypothesis is not here established, it seems desirable to advance it, if only to the end that the old and

commonly credited hypothesis may be more searchingly tested and made to show what truth there is in it, before it passes over into the sacred domain of accepted scientific fact.

Massive Equivalents of the Volcanic Ash.—The lava corresponding to the supposed ash of the Monterey series would doubtless be a very acid rhyolite, rich in soda. Such a rhyolite in the form of a dead white, massive rock occurs at Berkeley, as a flow mantling the eroded surface of the Cretaceous rocks, and overlaid by gravels, which are perhaps Pliocene. This Berkeley rock has been investigated by Mr. Charles Palache, and he finds it to be a soda rhyolite.* Now a very interesting fact is that pebbles of precisely the same rock as the soda-rhyolite at Berkeley are found in abundance in the ancient delta of the San Jose Creek at all elevations up to 620 feet above sea level. These pebbles prove that a massive rock corresponding in chemical character to the shale which constitutes the Monterey series exists in place somewhere in the hills which are drained by the San Jose. Neither the occurrence at Berkeley, nor that at the mouth of the San Jose, exceeds in elevation the summit of the Monterey series, and both occurrences may possibly have been submarine, for all that we know to the contrary.

Fossils.—Characteristic Miocene fossils have been found in the Monterey series at various parts of the coast by former observers, and in particular at the town of Monterey. These fossils are the warrant for the correlation of the series as Miocene. In addition to the various forms noted in the Geology of California, and in the Pacific Railway Reports, some fossils were found by us near Carmelo Bay which were submitted to Prof. W. H. Dall, who kindly examined them, and identified them as follows:—

Arca sp. (Nov.?)
Saxidomus sp.
Leda sp. (Nov.?)
Lucina, like L. Crenulata.
Clementia ? sp.
Young Cardium, or small Venericardia.
Pecten (Pseudamusium) Peckhami, Gabb.
Macoma sp. (Nov.?)

*See Bull. Dept. Geol. Univ. Cal., pp. 60–70.

On the summit of the hill between the San Jose cañon and Carmelo River, at an elevation of 800 feet, some fragments of bone were found in the chalky shale.

Distribution, Thickness, Structure, etc.—The areal distribution of the rocks of the Monterey series is very closely as it is represented on the map. The only condition which renders the precise demarkation of the western edge of the terrane difficult, is the fact that this edge is mantled with the variably thick terrace formations, and the latter are in places so thin that the underlying shale is apparent, so that it is not easy to say where the line between the two formations should be drawn. Our mapping, it will be noticed, is at variance with a statement made by Dr. Becker,* to the effect that "along the shore of Carmelo Bay Miocene schists have been locally altered to a cindery mass as if by the action of heat." This is an error; and the only rocks comparable to the description are the laminated lavas of carmeloïte described in detail in a subsequent portion of this paper. The geological survey of California seems to have entertained a notion with regard to these eruptives similar to that expressed by Dr. Becker. There are, however, no Miocene rocks along the shore of Carmelo Bay, neither are there any metamorphic rocks. Eastward and northeastward of Carmelo Bay the rocks of the Monterey series have an extensive distribution in continuity with the exposures within the limits of our map. They may be seen extending up the Carmelo on both sides of the valley for several miles in gently undulating folds, with a prevailing northeasterly dip at low angles (probably 10° on an average). On the road to the town of Monterey they are well exposed, with a prevailing northerly dip toward the Bay of Monterey at angles of from 5° to 10°.

As regards the thickness, only a minimum value can be obtained within the area examined. The hill between the Carmelo River and San Jose Creek presents an unbroken section of the shale from near sea level to its summit at 800 feet, and the dip of the strata is east northeast at angles ranging from 12° to 21°, thus showing directly, by mere inspection of the cliff (see section A-A′, Plate 1) that the local

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* Loc. cit.

thickness is over 1,000 feet. Farther up the Carmelo River, however, the greater height of the hills, taken together with the gently inclined attitudes of the strata, indicate a total thickness for the series of not less than 2,000 feet. The structural features of the series are of a simple character. As above stated, the strata as a rule are gently inclined to the horizon, and in places they are quite flat. Locally, however, there may be observed evidence of sharper flexure, as in the vicinity of the highest point on the coast road between Carmelo Bay and Monterey, where the dip for a short distance is at high angles and variable in direction, as if in the vicinity of a line of dislocation. The amount of disturbance which has affected the Monterey series is much less than that which is apparent in the case of the Carmelo series, as is evidenced by the absence of the minute shearing and the sharp, vertical folding which occur in the latter. This fact, and the equally significant one that the Carmelo rocks have been locally, completely eroded from the granite before the deposition of the shale of the Monterey series, so that the latter rests directly on the granite, serve to establish an unconformity between the two series, although they have not been observed in direct contact.

ERUPTIVE ROCKS.

Variation of Character.—The eruptive rocks in the vicinity of Carmelo Bay, although occurring in several separate areas, have a certain common feature which serves to stamp them as genetically identical, and their field relations in the different areas point to a single period of eruption. They exhibit, however, a considerable variation of character. Thus, in the same area, we may have the rock at one place perfectly massive and compact, and at another only a few hundred yards distant it will be found to be exceedingly vesicular or amygdaloidal, with amygdules occasionally two inches in length. In some cases a very pronounced flow structure is apparent, and in others no such structure has been developed. In some localities there is a distinct lamination of the rock, accentuated by contrasting colors, while in the same mass not far distant no lamination is apparent. There is also an extensive range of aspect due to the varying degree to which weathering influences have affected the

various facies. The fresh rocks exposed in the sea cliffs are usually of a dark bluish gray color, while the sub-aerially weathered portions are of a yellowish or pinkish color, or have a bleached appearance. Sometimes they are rusty or ocherous on the surface. Some varieties have a yellowish or greenish gray color on the freshly broken surface.

The variation is, moreover, not confined to the macroscopic features of the rock. When viewed in thin section on the stage of the microscope, or when investigated chemically, it is far from uniform in character. Glass is abundant in some sections, while others are more nearly holocrystalline. Among the porphyritic constituents augite and plagioclase vary much in the proportion in which they are present. In most facies one or both of these minerals may be lacking among the phenocrysts. Chemical analysis has shown that the silica content has a range of at least from 52 per cent. to 60 per cent., the former figure being usually regarded as too low for the andesites and the latter as too high for the basalts. There is thus some trouble in properly classifying them in the current petrographical schemes. In consideration of this fact and of their very peculiar mineralogical character, these rocks will be referred to in this paper under the name *carmeloïte*, their strong individuality being ample warrant for the new name.

The common characteristic of all facies of these eruptive rocks is the presence, as a phenocryst of a mineral which, by reason of its rarity and the obstacles to investigation which it presents, has received but little attention at the hands of petrographers and mineralogists. So scant are the references to it in mineralogical literature that, notwithstanding its distinct specific character, it has not yet been signalized by a name. The most extended and satisfactory note that has yet appeared regarding it is by Prof. J. P. Iddings,* in a work which has recently been published and which reached the writer after this investigation on the mineral in question had been completed. For this reason and also in recognition of Professor Iddings' eminent services to the science of petrography, it is proposed to name the mineral *iddingsite.*

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*Geology of the Eureka District, Nevada. Monograph XX U. S. G. S., Appendix B, pp. 388–390.

The Rock-Forming Mineral, Iddingsite.—In order to establish the specific character of iddingsite it will be convenient to state the results of our observations upon it somewhat in detail, before entering upon the more general description of the carmeloïte in which it occurs. Macroscopically iddingsite may be observed in those facies of the carmeloïte in which it is best developed to be a mineral having a lamellar structure due to a very facile cleavage. The cleavage lamellæ are very brittle and break off sharply in fracture planes transverse to the cleavage. (See Plate 4, Fig. 1.) It scratches selenite with ease, but may be crushed to powder on a cleavage surface of Iceland spar, by rubbing with a soft wooden point, without scratching the spar. Its hardness may therefore be placed at about 2.5. Its prevailing color is bronze, and the cleavage faces have a pronounced bronzy metallic luster. Other colors, however, are frequently exhibited, ranging from light brown to deep brownish red. Its maximum specific gravity is 2.839 as determined by the aid of Klein's solution; but it varies in this property, and different lower values may be obtained for different portions of the powdered mineral, a fact which renders its separation from the other constituents of the rock a matter of great difficulty. Before the blowpipe it is infusible and is not perceptibly altered. It is very readily decomposed by hydrofluoric acid. When fragments are treated with hydrochloric acid, the application of a little heat immediately effects the extraction of the iron, without otherwise decomposing the mineral or affecting its action on polarized light. Continued digestion of the mineral in the form of powder ends in its complete decomposition with the separation of pulverent silica. It decomposes perhaps even more readily in sulphuric acid, also with the separation of pulverent silica. When heated in the closed tube, the powder yields water, but less abundantly than a similar quantity of powdered serpentine.

The solutions in hydrochloric and sulphuric acids were examined chemically, after the removal of the pulverent silica by filtration, and abundantly satisfactory reactions were obtained for iron, lime, and magnesia. No aluminum was detected. Moreover the flame test in very numerous experiments showed the constant presence of sodium. Chemically, therefore, iddingsite is a hydrous non-alum-

inous silicate, of iron, lime, magnesia, and soda. The easy extraction of iron by acids without decomposition of the mineral indicates that a considerable proportion of that element is present, not as part of the silicate molecule, but as a pigment in the form of hematite or limonite, probably the latter.

The *form* of the crystals of iddingsite, as seen in hand specimens of the carmeloïte with the aid of a lens, is found very generally to be conditioned by: (1) The cleavage representing one pinacoid; (2) two pair of prismatic (dome) faces at right angles to the cleavage, and intersecting in an angle, the average value of which for several rough measurements is about 80°; and (3) a pair of pinacoidal faces also at right angles to the cleavage and parallel to the longer of the two axes which lie in the cleavage plane. The general form of the cleavage fragments is shown in Plate 4, Fig. 1. Owing to the softness, brittleness, and eminent cleavage, complete crystal forms cannot be detached from the rock for examination, and every attempt in this direction yields at best only oblong hexagonal cleavage plates bounded by these prismatic (dome) and pinacoidal faces. The full form may, however, be largely inferred from the character of the sections of the idiomorphic forms revealed in the microscopic preparations of the rock. These cross sections are remarkably similar to those which are characteristic of olivine, and at once suggest that iddingsite is a pseudomorph of that mineral. In all references that have been found to this mineral, or to any mineral analogous to it, the writers have invariably regarded it as a result of the alteration of olivine.*

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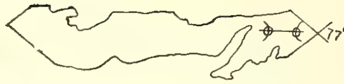
*Most of these references are discussed by Iddings, loc. cit. They are as follows:—

(1) Dana, Jas. D., "System of Mineralogy," 5th ed., page 465. Description of the mineral thermophyllite, a form of crystallized serpentine. Also *ibid*, 6th ed., p. 670. The description given of thermophyllite does not accord with that of the characters of iddingsite in several critical particulars.

Again, *ibid*, 5th ed., p. 258, we have the following statement: "Alteration of chrysotile often takes place through oxidation of the iron; the mineral becomes brownish or reddish brown and iridescent. It also splits into thin laminæ as the change goes on, sometimes so as to resemble mica. A basalt was once pointed out to the author as a mica slate, although no farther change had taken place than that here mentioned." This statement as to the development of a lamellar structure is omitted in the recently issued 6th edition.

1



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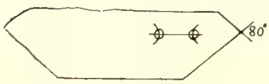

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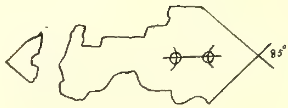

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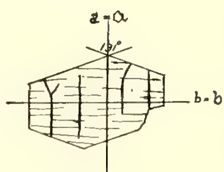

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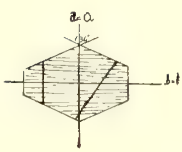

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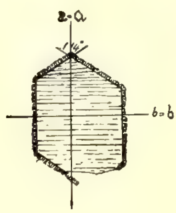

8

1. Cleavage Fragment of Iddingsite.

2, 3, 4, 5. Sections of Iddingsite Parallel to the Cleavage and Perpendicular to the Acute Bisectrix. a

6, 7, 8. Sections of Iddingsite Approximately Parallel to the Basal Pinacoid, (001), Showing Cleavages and Cracks. In 8 the Heavy Border Represents a Peripheral Wreath of Green Serpentinous Matter.

In deference to these views, and in order to facilitate comparisons, it will be convenient to give its crystallographic axes a position in space corresponding to that of olivine. Now, if we consider the form of the most common cross sections exhibited in the slides, we find that there are two pronounced types, viz.: (1) A set of cross sections which may be easily recognized as parallel to the plane of eminent cleavage. These are represented by Figs. 2, 3, 4, 5, Plate 4. (2) A set of cross sections which are transverse to the cleavage, Figs. 6, 7, 8, Plate 4. The latter correspond in form to the basal sections of olivine, while the former correspond to a pinacoidal section. In the basal sections, moreover, the cleavage traces subtend the large prismatic angle 110 $\wedge$ 110 = 130°, and is therefore in the plane of the macropinacoid. We have thus the following for our crystallographic scheme: $\bar{b}$ in the cleavage plane, $\breve{a}$ perpendicular to the cleavage, and $\acute{c}$ in the cleavage and parallel to elongation of the crystals. This statement that the cleavage corresponds to the macropinacoid (100) is at variance with that of Michel-Levy and Lacroix, who affirm that the cleavage of the decomposition product to which they refer is parallel to the brachypinacoid (010).* They also state that the optic axis appears to be situated in the plane of the cleavage. In iddingsite it is normal to the cleavage. the optic axial plane

The orthorhombic symmetry of iddingsite, which is assumed in the above comparison with olivine, is proved by its optical character. Under the microscope the cleavage plates prove to be biaxial and yield with great definiteness an interference figure which shows that the plane of the optic axis is at right angles to the cleavage,

(2) Zirkel F., Basalt gesteine Bonn, 1870, p. 65, also Microscopical Petrography of the 40th Parallel, Wash., 1876, p. 230.

(3) Rosenbusch, Mikroskopische Physiographie, Stuttgart, 1877, p. 400.

(4) Michel-Levy et Lacroix, Les Minéraux des Roches, Paris, 1888, p. 248: "L'olivine se transforme en serpentine, ou en un corps ferrugineux rouge par transparence, à clivage facile suivant g' (010) dont les axes optiques paraissent être situés, à l'inverse du peridot dans un plan de la zone d'allongement. Parfois ce produit d'alteration est polychroique."

*Loc. cit. The position of the axis of olivine in the *Mineraux des Roches* is not the same as that in German, English, and American works, $\breve{a}$ and $\acute{c}$ being transposed. But the adjustment of this difference of usage would not reconcile the two statements. 3

and parallel to the $\dot{c}$ axis, and that the acute bisectrix is perpendicular to the cleavage, being coincident with the $\breve{a}$ axis. The cleavage plates exhibit a pronounced fibrous structure parallel to $\bar{b}$. In these plates and in all sections transverse to the cleavage in the slides, the extinction is strictly parallel to the cleavage, to the transverse fibrous structure, and to the traces of the pinacoids. This shows that the three axes of elasticity are parallel to the three crystallographic axes respectively, and that the mineral is therefore orthorhombic.

Since the plane of the optic axes lies in the brachypinacoid $\mathfrak{b} = \bar{b}$. By the aid of the quarter-undulation mica plate, in sections parallel to the cleavage, and the quartz wedge in sections parallel to the optic axial plane, it was ascertained that the crystals were optically negative. Therefore the axis of maximum elasticity is the acute bisectrix; so that $\mathfrak{a} = \breve{a}$, and $\mathfrak{c} = \dot{c}$.

In thin section iddingsite becomes transparent in colors which range from a deep chestnut brown to citron yellow, or occasionally a clear yellowish green. The pleochroism is strongly marked in sections transverse to the cleavage, particularly so in those parallel to the optic axial plane, but is usually very feeble in sections parallel to the cleavage. The absorption formula is $\mathfrak{c} > \mathfrak{b} > \mathfrak{a}$.

The interference colors, between crossed nicols, for sections parallel to the cleavage (macropinacoid) do not differ perceptibly from those observed with the analyzer removed, except that a slight decomposition of the light due to the fibrous structure becomes apparent. In the most favorable sections parallel to the optic axial plane, however, interference colors are bright green and carmine tints, almost like those of muscovite, to which resemblance the eminent cleavage adds greatly. The double refraction is thus strong. The mean index of refraction is low.

No mineral answering to the combination of characters above detailed can be found described in the books. The external form of the crystals at once suggests that of olivine. But the chemical, optical, and other physical characters separate it absolutely from olivine. And the only question in this connection which can arise is, whether or not iddingsite is a pseudomorph or alteration product of olivine. It seems to us that the evidence is far from con-

clusive on this point. No trace of olivine or of its ordinary decomposition product has been detected in our slides. The chemical character of the mineral is moreover not in harmony with the suggestion of its derivation from olivine. Both calcium and sodium are present in notable amounts, and it is difficult to understand how these could occur in an alteration product of olivine.

It is evidently not the form of crystallized serpentine, thermophyllite, since it differs from the latter in physical appearance, in its behavior before the blowpipe, in density, in luster, and in color; neither does it correspond optically with serpentine. Moreover, the development of serpentine from olivine by hydration is accompanied by a swelling of the mass. In the case of iddingsite, on the contrary, there is very frequently excellent evidence of shrinkage. This is clearly seen in the spaces along the cleavages, which are often so open as to constitute a very large proportion of the total space occupied by the phenocryst. There appears thus to be no good reason for regarding the mineral as a crystallized variety of serpentine. In the great majority of the many cases examined the mineral is perfectly homogeneous, optically and physically. It is only heterogeneous in so far as the pigment, which is not a part of the silicate molecule, is unevenly distributed. It is, as Professor Iddings observes, in no sense an aggregate pseudomorph. It is, however, not entirely free from decomposition products. In one slide a few crystals were observed which had in part decomposed to calcite, as was proved by treatment of the section, on the stage of the microscope, by very dilute cold hydrochloric acid. The material which was submitted to qualitative analysis was, however, quite free from such decomposition products, and the lime was, without question, part of the silicate molecule. It seems, then, that, in spite of the similarity in form to olivine, there is serious doubt as to its derivation from that mineral. The poverty in magnesia, shown by two analyses of the carmeloïte, strengthens this doubt.

Two other possibilities as to the origin of iddingsite merit consideration: (1) It may be a pseudomorph, after another mineral of the same crystallographic habit as olivine, such as monticellite, or (2) it may be an original separation from the magma but little altered. The total absence of any trace of a non-lamellar mineral

from which it might have been derived by process of alteration seems to favor the latter possibility. In this case, however, we should expect that the water yielded in the closed tube would be derived from the limonitic pigment, which is not a part of the silicate molecule. To test this the following experiment was made: A small quantity of the mineral, in minute fragments, was digested in hydrochloric acid till the brown color was discharged, and the iron, so far as could be judged, was leached out. Some of the fragments were then tested optically, and were found to give the same reactions as before treatment. The fragments were then dried, powdered, dried again for several hours at 100° C., and then tested for water in closed tube, with an affirmative result. The experiment shows that, although a portion of water is doubtless present in the form of limonite, there is also a portion which remains after the latter is removed, and is part of the silicate molecule.

The Sunium Point Eruptive Area.—A glance at the accompanying geological map will show that the carmeloïte in the vicinity of Carmelo Bay occurs in six separate patches. The map being a sufficient account of the distribution of these patches and of their extent, we will proceed, without dwelling on these matters, to describe the rock in detail, taking up the different areas or patches in succession. The most interesting of these areas, if not the largest, is that which occupies Sunium Point and the shore to the northeast and east of it, to the extent mapped. The extremity of Sunium Point is composed of a dense, compact rock, having a bluish gray aphanitic base, throughout which are scattered numerous small phenocrysts of feldspar and iddingsite, the latter of a deeper red color than it ordinarily presents, and showing the usual lustrous cleavages. The size of these phenocrysts of iddingsite rarely exceeds a millimeter in length, and they commonly range from about .25 to .5 mm. The phenocrysts of plagioclase may be as much as 2 mm. in length. Under the microscope the ground-mass of this rock appears to be a fine feltwork of lath-shaped plagioclase, with numerous minute granules of magnetite, and of a rather brightly polarizing mineral (pyroxene). In addition to these there are also numerous rod-like microlites, which with low powers appear to be opaque, but which under higher powers are in some cases feebly

translucent in dark brown colors. The ground-mass is not uniform in texture. Some parts, constituting definite areas in the section, are very dense, and are crowded with opaque granules, while the surrounding parts are coarser and more transparent. The denser areas appear to be of earlier consolidation, since the feldspars of the more transparent portions of the ground-mass show a tangential disposition with reference to them. Glass is present in the ground-mass, and in it are very numerous feebly polarizing globulites of higher refractive power. In most of the slides from this locality no iddingsite can be detected in the ground-mass. In one slide, however, a few minute shreds of this mineral were found to constitute a part of the ground-mass. In addition to the phenocrysts observed macroscopically, augite is also revealed in thin sections. The augite is frequently nearly colorless, but has a faint reddish or violet reddish tinge. It is perfectly fresh, and is sharply idiomorphic, showing in sections transverse to the prism the characteristic octagonal outlines, with nearly rectangular cleavages. Twinning is common on the orthopinacoid. The plagioclase phenocrysts are also perfectly fresh and glassy. They show in some cases a distinct zonal structure. The twinning lamellæ are usually broad, and the value of the extinction angle, when this is nearly the same for odd and even numbered lamellæ on opposite sides of the cross hair, indicates that the feldspar is labradorite. In some instances the labradorite and augite are associated in ophitic aggregates. The iddingsite is abundant in all sections.

In addition to the general description of this mineral given in the previous pages, some local features may be noted. The color is not constant. The prevalent color is a deep chestnut brown, but in a few cases the same mineral is of a clear yellowish green, as if quite free from limonite pigment. This variety has the same absorption and other optical characters as the brown varieties. In the green varieties the color is usually uniform, but in the brown crystals the coloring pigment is often distributed in streaks and in irregular patches of varying depth of color. In other sections the brown color is uniform, and in some of these the pigment is so dense as to render the mineral scarcely translucent. Both the brown and the green varieties were observed in one slide to be

partly replaced by calcite. Certain other nearly colorless, grayish decomposition products of an indeterminate character also appear in the same slide. These polarize as an aggregate. Certain specimens from another locality on the shore are interesting as showing various stages of decomposition of iddingsite to serpentine (?). The alteration seems to begin in the center most commonly. Crystals may be observed with idiomorphic boundaries, which in their central portions consist of a greenish fibrous mineral. This green product is very feebly polarizing, and sometimes is practically isotropic. In some cases it polarizes as an aggregate. The peripheral portions of the same crystal are normal iddingsite. In other cases the entire phenocryst is replaced by the green material. In some cases, also, the iddingsite has acquired a green color without losing its characteristic optical properties. There is also a varying proportion of the green matter in small patches or elongated shreds scattered through the ground-mass.

A chemical analysis of a representative sample of the carmeloïte from Sunium Point gave the following results:—

$Si\,O_2$	52.83
$Ti\,O_2$	trace
$Al_2\,O_3$	17.67
$Fe_2\,O_3$	7.50
$Fe\,O$	1.68
$Ca\,O$	7.35
$Mg\,O$	2.47
$K_2\,O$	2.52
$Na_2\,O$	6.61
Ignition	2.32
	100.95
Sp. g.	2.80

On the shore east of Sunium Point the same rock presents other facies. It is here thinly bedded, shows in places a contorted structure, due to viscous flow, has intercalated agglomerates, and is strongly vesicular or amygdaloidal. This amygdaloidal facies differs from that of Sunium Point in its microscopic aspects in the preponderance of glass in the ground-mass. The

magnetite, moreover, does not seem to have been individualized, but to have remained in the glass as a dusty material, rendering it nearly or quite opaque. No augite was observed, and the clear green varieties of the iddingsite phenocrysts are here studied to best advantage. The vesicles are usually flattened in the planes of flow. The amygdules consist commonly of chalcedony, calcite, and chlorite.

The Ravine Area.—About a mile due east of Sunium Point, the seventeen-mile pleasure drive passes through a narrow ravine. Along the sides of this ravine there is exposed beneath the terrace formations a large oval area of carmeloïte, which is well seen in the rock cuts along the drive. The area may be so extensive as to merge with the Sunium Point area beneath the newer formations; but there are certain local peculiarities which suggest that it is a somewhat different flow. These differences are not so pronounced macroscopically as they are microscopically, owing to the vagaries of weathering. Under the microscope the rock of the ravine area differs from that of Sunium Point chiefly in the absence of phenocrysts of augite, the notable amount of glass, and the presence of iddingsite in the ground-mass in comparative abundance. In some of the slides in which iddingsite is abundant, this mineral assumes a habit which is not observed in the carmeloïte from other localities. The forms seen in cross section are prevalently long and rectangular; and the oblong character seems to be due to the excessive elongation of the crystals in a direction perpendicular to the cleavage, *i. e.*, parallel to the axis $\mathfrak{a}$. These crystals have a bleached aspect, and are colorless; or are clear, light greenish yellow, or cloudy, brownish gray in color. The pleochroism is, however, pronounced, with the same absorption formula as in the normal phases of the mineral. The interference colors between crossed nicols in these pale iddingsites, are brilliant green and pink, not unlike those of muscovite. The cleavage is exceptionally well developed. The shrinkage of the mass of the original crystal is also excellently well shown in these sections by the spaces between the cleavage lamellæ. The only other local feature of special interest presented by this mineral is its occasional occurrence as a core of deep brown color surrounded by a peripheral area of light greenish

substance, as if alteration were proceeding by a discharge of the iron oxide. This greenish substance is in part, at least, secondary, and different in its optical behavior from the green varieties of the iddingsite; it is probably serpentine.

In some of the slides the phenocrysts of plagioclase are much larger than those in the rock of the Sunium Point area, and in others phenocrysts of this mineral are absent. The difference may be due to the fact of specimens having been taken from different flows, but whether this was the case or not could not be recognized in the field. In those cases where there are large phenocrysts of plagioclase, the latter are frequently charged heavily with inclusions which resemble closely the finer portions of the ground-mass in the immediate vicinity of the phenocryst. Sometimes this included matter is arranged peripherally, while in other cases it is central, or is evenly distributed throughout the entire section of the phenocryst. A little chalcedony was detected in some of the slides; but this, together with quartz, is abundant in the form of amygdules in the amygdaloidal facies of the rock.

In the ground-mass of these sections, also, there is in addition to the magnetite a considerable amount of minute granules of a deep brownish red translucent mineral (limonite). The iddingsite of the ground-mass is usually greenish yellow in color, and occurs in shred-like patches devoid of crystallographic boundaries. It lies between the plagioclases in the ground-mass, and does not exceed the latter in size. It seems to bear an ophitic relation to the plagioclase. It is distinctly pleochroic, has parallel extinction, low refractive index, strong double refraction, and otherwise resembles the paler varieties of the phenocrysts of the same mineral.

The Abalone Point Area.—On the north side of Abalone Point there is an area of perhaps ten acres of carmeloïte, abutting against the granite on the one side, and passing beneath the terrace formations and blown sand on the other. The rock is often much decomposed, appearing as a purplish red, earthy mass in which the original character of the formation can be recognized only with great difficulty. The fresher portions present at least two distinct facies. One of these is a dense bluish rock with irregularly parallel streaks of greenish yellow through it. The other is nearly uniformly of a

greenish yellow color, resembling an epidotic rock. In both facies phenocrysts of iddingsite are abundant; and microscopic examination shows that there is no other phenocryst present. The iddingsite is heavily charged in most cases with iron oxide. In the greenish yellow variety the ground-mass is as usual chiefly a feltwork of minute lath-shaped crystals of plagioclase with perhaps some interstitial glass. In addition to this there are, however, considerable quantities of a yellowish pleochroic mineral showing a longitudinal monotomous cleavage (apparently fibrous in some instances) and parallel extinction. It is the presence of this mineral which gives the greenish yellow color to the rock. Its minute dimensions render its determination difficult, but it is believed to be a later generation of the iddingsite in the ground-mass. Magnetite is also present in granules.

In the blue variety of the rock the ground-mass is the same as in the other, except that there are only a few scattered shreds of the yellow, pleochroic mineral just mentioned. There are also vesicular and amygdaloidal varieties, which are less dense in texture, and are often limonitic. In addition to the facies above described, there are at the Abalone Point area beds of volcanic agglomerate and of breccia which have not been examined microscopically.

The Lagoon Area.—At the north end of the bar, which, throughout most of the year, shuts off the water of the Carmelo lagoon from the ocean, a patch of carmeloïte still smaller than that at Abalone Point emerges from beneath the sand. Macroscopically it is a light brownish or yellowish gray rock with distinct lamination planes along which the rock tends to split when struck with the hammer. The surfaces of this lamination plane have a greenish yellow aspect, due to the abundance of a mineral of that color in the vicinity of these planes. Iddingsite is the only phenocryst present, and the crystals are large and well formed.

Microscopically this facies of the rock is chiefly interesting for the definiteness with which iddingsite may be recognized in the ground-mass. The ground-mass is essentially glass charged with minute lath-shaped crystals of plagioclase, and small, ill-defined crystals of iddingsite, recognizable by their color, pronounced pleochroism, characteristic cleavage, parallel extinction, etc. There

are in addition a few scattered granules of magnetite. An analysis was made of the rock, and although the total foots up too high, the results are valuable and of interest. The analysis shows that the rock contains 60 per cent. of silica, and it has a low specific gravity. The abundance of glass, the high proportion of silica and water, and the small amount of iron, serve to explain the great contrast in the density of this facies with that of Sunium Point. The amount of silica is greater than that usually found in the rocks classed as basalts; chemically it falls in with the andesites.

Analysis of carmeloïte from the outcrop at the Carmelo lagoon.

$Si\,O_2$	60.00
$Al_2\,O_3$	19.01
$Fe_2\,O_3$	3.20
$Fe\,O$	0.68
$Mn\,O$	trace
$Ca\,O$	4.10
$Mg\,O$	1.28
$K_2\,O$	2.79
$Na_2\,O$	6.97
Ignition	4.30
	102.33

Specific gravity 2.51 to 2.54.

The Mission Area.—A low hill between the Carmelo Mission and Mrs. Martin's farmhouse is occupied to the extent of a few acres by a peculiar facies of the carmeloïte. It has a prevailingly light purplish blue color, and has a very distinct laminated appearance, due to the banding of the rock with thin purplish brown layers. This banding is not uniform in character. When it is best displayed the brownish layers are about a millimeter thick, and are several millimeters apart. The rock tends to split parallel to the lamination. Sometimes the banding is absent. Locally, also, the mass may present a whitish bleached aspect. Phenocrysts of iddingsite are usually abundant. Microscopically the ground-mass consists of a feltwork of plagioclase and iddingsite, with scattered grains of magnetite and considerable interstitial glass. The purplish blue portions of the rock are represented in the slide by areas rich in black

iron oxide, while the brownish laminæ owe their color to the preponderance of brown iron oxide. In both areas the iron oxide, whether black or brown, appears to be associated with the iddingsite of the ground-mass; and in a series of slides all gradations may be traced from crystals which are nearly or quite opaque, from dense pigment, to those which are transparent, with only a little yellow oxide associated with them peripherally. Throughout the ground-mass, also, there may be seen in some of the slides, small, hazy, greenish areas, which appear to be chlorite or serpentine.

Imbedded in the ground-mass are large, well-formed crystals of iddingsite, which are usually sufficiently free of pigment to allow of satisfactory study of their optical character.

The San Jose Area.—A crescent shaped area of carmeloïte encircles the head of the sharp, short cañon which gashes the hill immediately to the north of San Jose Creek near its mouth. The rock here is usually of a greenish gray or purplish gray color, mottled with white spots representing phenocrysts of plagioclase, and also in some cases with larger irregular blotches of yellow limonite. Phenocrysts of iddingsite may also be detected, but they are not abundant.

Under the microscope it is found to consist of the usual ground-mass of lath-shaped plagioclase and iddingsite, with interstitial glass and scattered granules of magnetite. In addition to the latter ore, however, there is an abundance of limonite, both in small granules and in large, irregular patches. The iddingsite in this ground-mass shows, perhaps, more definitely than in other cases an ophitic relation to the lath-shaped plagioclase. Imbedded in the ground-mass appear phenocrysts of fresh plagioclase and of iddingsite. The presence of the phenocrysts of plagioclase allies the facies rather with the occurrences at Sunium Point or the ravine area than with those at Abalone Point, the lagoon, and the mission.

Relation of the Carmeloïte to Other Formations.—Having described the petrographical character of the carmeloïte, a word remains to be said as to its structural and time relations to the other formations of the vicinity. The petrographical description establishes its igneous character. The flow structure, the occasional bedding, the presence of agglomerates and breccias, the vesicular

and amygdaloidal habit, and the prevalence of glass in the ground-mass show that portions at least of the masses here described are surface lava flows. That the *whole* of the carmeloïte exhibited in the different areas is of the character of a lava flow cannot be positively affirmed. Indeed, there is evidence that not only have we the lava as extruded in approximately horizontal sheets at the surface, but also that a portion of one of the masses occupies a position in the vent from which the surface flows emanated. Thus on the northwest side of Sunium Point there is a vertical plane of contact between the carmeloïte and the conglomerates of the Carmelo series. A careful inspection of this contact shows clearly that the carmeloïte is eruptive through the conglomerate, portions of the latter being inclosed in the igneous rock. Thus it would appear that the mass of carmeloïte which occupies the extremity of Sunium Point is of the nature of a volcanic plug. In direct continuity with the mass are rocks on the shore east of Sunium Point, which have intercalated agglomerates and are thinly laminated; they also show flow contortion and vesicular and amygdaloidal structure, with the amygdules flattened in the planes of flow, the latter being at low angles with the horizon, dipping seaward. These are undoubtedly surface lavas. Comparing the plug rock with the surface flow in this and the other areas, an interesting fact comes out. The plug rock of Sunium Point is the only facies of this volcanic formation in which phenocrysts of augite are present. In the plug rock these augites abound; in the surface lavas they have not been observed. The glass is not so abundant in the plug rock as in the surface flows, and it differs from the latter, also, in having very numerous globulites present in the ground-mass. As regards the chemical relations of the two facies, only two analyses of carmeloïte have been made. One of these, however, is of the plug rock, and the other of a surface flow at the lagoon area, and results are of much interest (see analyses, pp. 38, 42). The plug rock contains only 52.83 per cent of silica, and has a specific gravity of 2.80, while the surface flow contains 60 per cent of silica, and has a specific gravity of 2.51 to 2.54.

The intrusion of the conglomerates of the Carmelo series by the carmeloïte at Sunium Point establishes the age of the latter as certainly later than that series. Both the plug facies and the lava

facies of the rock are overmantled in the vicinity of Sunium Point by the lower (*i. e.*, newer) terrace formations.

At the ravine area the only relation which can be satisfactorily established is the unconformable superposition of the terrace formations upon the lava, fragments of the lava being found in the sandstone. Stratigraphical considerations, however, render it highly probable that the lava of the ravine area is above the shales of the Monterey series. A fact of considerable interest is very apparent in the ravine section. The lava is seen to have been sharply faulted, and the superposition of the terrace sandstone upon the lava shows clearly, as appears in the accompanying diagram, Fig. 3, that this faulting has occurred *subsequent to the deposition of the terrace formations.*

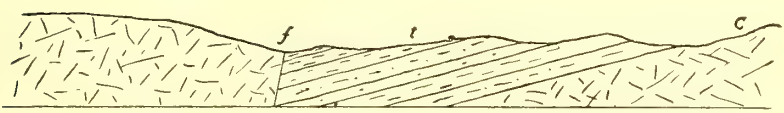

FIGURE 3.—Section on carriage drive in the ravine, showing terrace formations reposing upon carmeloïte lava, and both faulted; *c*, carmeloïte; *t*, terrace formations; *f*, fault. Scale 60 feet = one inch.

At Abalone Point the carmeloïte lava is in sharp contact towards the west with the Santa Lucia granite. So much secondary decomposition has taken place along the zone of contact that it is difficult to determine whether the contact is due to faulting or is of an intrusive character. It was our opinion in the field that the phenomena appeared to be rather those of faulting than of intrusion. The supposition of the intrusive character of the contact is negatived by the lava-like character of the carmeloïte close up to the granite, and by the presence of agglomerates and breccias interbedded with the lava. The relative age of the carmeloïte and granite is directly established by the occurrence of rounded bowlders of the latter imbedded in the lava.

No contacts of the eruptive masses with older rocks are observable at the lagoon area or at the mission area.

Thus far the age of the eruptive rocks has only been roughly limited to the following extent: 1. They are later than the Carmelo

series. 2. They are probably later than the Monterey series. 3. They are older than the newer terrace formations, which mantle the lower slopes of the coast.

When we come to the San Jose area, however, evidence is presented which enables us to locate with great precision the relative age of the eruption. Here we find a sheet of carmeloïte lava, amygdaloidal in places, and about 60 feet thick, intercalated with the terrace formations, conforming to their attitude and clearly contemporaneous in origin. The gravels and conglomerate here represent an ancient delta of San Jose Creek when the land was several hundred feet lower than at present; when the delta was partially built up to the dimensions which it eventually attained, the lava was poured out over its surface, and was then buried by subsequent accumulations. The portion of the lava sheet now revealed mantled the outer edge of the delta surface where it began to pitch steeply into deep water, and the lava flowed over this steeply sloping edge of the accumulating gravel. Thus the age of the carmeloïte lava is definitely located as contemporaneous with that stage of the delta-forming depression at which the land had reached an altitude of 400 to 500 feet lower than at present. The lavas which flowed over lower slopes and were mantled by the terrace gravels of successive stages of the subsequent uplift, were, therefore, submarine flows, a fact which may in future prove of much interest petrologically, in comparisons of subaerial and submarine lavas.

THE ANCIENT BASE-LEVELS OF THE COAST.

Ancient Ocean Strands.—The abundant evidences of the former occupation by the sea of the coastal slopes of Carmelo Bay are among the most interesting and attractive features of the geology of the region. Up to elevations of at least 800 feet above the present sea level there may be observed various distinct strands of the ocean in the form of terraces, a beach, a delta, sea-cliffs with Pholas borings and marine formations of sand, clay, sandstone, incoherent beach pebbles, and compact, cemented conglomerates. The terraces are not confined to the coastal slope, but extend up the valley of the Carmelo River for many miles. These may be seen to advantage from the sand bar at the mouth of the river in an early morn-

ing light, those on the north side of the valley being particularly distinct from this point of view.

Huckleberry Hill Beach.—The highest strand yet observed by us is best registered on Huckleberry Hill, a little to the north of the northern limits of our map. In coming from Monterey towards Carmelo Bay over the main coast road there is a steady upward grade for something over two miles to a wind gap at an elevation of about 585 feet. At this point the seventeen-mile pleasure drive leaves the main road by a gate. Running out west-northwestward from this wind gap is a ridge which increases in elevation for about a mile and then drops away abruptly to a plain which encircles the end of it, several hundred feet below. Over the surface of this ridge, which is rather flat-topped in north and south profile, are scattered pebbles and bowlders, very sparingly at first, but more and more abundantly as one goes westward. There is also a sandy soil containing fragments of rock foreign to the underlying formations, and occasional outcrops of a yellow plastic clay may be observed. Towards the end of the ridge, with the increasing elevation, the pebbles and bowlders increase in numbers till they finally culminate in a well-defined round-topped beach, the crest of which is 800 feet above the tide. A large opening or pit has been made in the beach, the material being used for ballast on the roads of the vicinity, so that the composition, structure, and relations of the beach are happily revealed. The material composing it consists of water-worn pebbles and bowlders, many of the latter being a foot or more in diameter. The rocks represented by the pebbles are various, but granite (Santa Lucia) preponderates greatly, that being the underlying terrane. These pebbles and bowlders of granite, which necessarily must have been fresh and hard when left by the wave action on the beach, are now nearly all rotten and disintegrated. It is this rotten product of the secular decay of the pebbles and bowlders which is quarried for road ballast, being easily worked with pick and shovel, while the occasional harder bowlders are left on the floor of the pit. Among the smaller undecomposed pebbles were gathered numerous pieces of the white shale of the Monterey series, fragments of granite similar to that of the small dykes which intersect the Santa Lucia mass, fragments of pegmatite from the dykes which cut the same mass,

numerous pieces of white quartz, and of vitreous quartz, fragments of quartzite, and one piece of a dense light-colored rock, probably a rhyolite. All of these are perfectly water worn. In structure the beach presents the confused accumulation characteristic of beaches. There are no stratification or structural planes of any kind apparent. The beach appears to rest directly upon the surface of the granite which is revealed in the lower slopes of the ridge. The altitude of this beach, 800 feet, was determined by a large aneroid barometer checked half an hour later on a known elevation on the Coast Survey chart, and an hour later at sea level, both checks being in agreement.

Ancient Delta of the San Jose.—Of a somewhat different order are the evidences of coastal oscillation afforded by the ancient delta of the San Jose Creek. The location, altitude, and extent of the lower portion of this delta are represented on the map with a very fair degree of precision. As there indicated, the delta occupies a triangular area on the north side of the present cañon of the San Jose, and mantles a sloping surface of the Santa Lucia granite and the shale of the Monterey series. The highest point of the delta is 620 feet, and the delta formation spreads out fan-like down the antecedent slope to within less than 100 feet above tide. The delta is composed very largely of incoherent stream detritus, the pebbles being chiefly granite, quartz, white rhyolite, and some few pebbles of the white shale of the Monterey series. The upper portion of the delta is coarse and shows little or no assortment of the detritus; the lower portion, which spreads downward over the slope of the hill, is less coarse and more sandy in character, and shows bedding, with a steep seaward dip. These beds are also partially consolidated into light gray to yellowish sandstones.

The delta as mapped is not the product of any single stage in the varying relations of sea and land, but has had a somewhat complex history, all the details of which have not been unraveled. The upper portion of the delta has been dissected by the San Jose Creek and by a small tributary creek which comes in on the north side just east of the limits of the area mapped. This dissection, together with the degradation of the delta by ordinary subaerial erosion, reveals some facts of interest. The most striking of these facts is

that the delta is divided into two distinct portions by a sheet of carmeloïte lava, which has a maximum thickness of about 60 feet. The edge of this lava sheet is well exposed, encircling the head of a small, sharp cañon which is being rapidly excavated out of the delta material that underlies it. This small, sharp cañon is held in on either side by a granite ridge, and probably represents an old channel of the San Jose. On the walls of this little cañon the structure of the lower or pre-volcanic part of the delta is well shown. The material is stratified as a coarse conglomeritic sandstone, with a dip too steep probably for an angle of deposition, even on the outer edge of a delta, and the lava sheet is approximately conformable to this attitude of the strata, thus suggesting a slight local disturbance. The lava sheet, however, does not rest entirely upon the lower delta. In part it reposes directly upon a level terrace-like ridge of the Santa Lucia granite which has an elevation of 500 feet. This terrace-like ridge seems to be the remnant of an old sea terrace. The lava sheet, where it rests upon the granite ridge, between the little cañon above mentioned and the gorge of the San Jose, is only a few feet thick, but whether this rapid reduction in the thickness of the sheet is an original feature or is due to subsequent stream action could not be determined.

From its lower edge the delta extends up the valley of the San Jose for a known distance of over a mile, and it probably extends much farther. At the distance of a mile up the valley, on the ridge between the San Jose and the northern tributary, the delta is about 175 feet thick and reposes upon a floor of granite which has an elevation of about 265 feet. This material is chiefly very irregularly bedded incoherent sandstones and gravels. From its petrographical characters and its position it is thought to be the same formation as that which nearer the ocean appears beneath the lava sheet. In fact, just across the gorge of the tributary is a small patch of lava resting on granite at an elevation just sufficient to cover this material if extended; and it seems probable that a fairly large sheet of lava has been removed in the process of the dissection of the delta. As this delta material is well within the cañon of the San Jose, with high walls on either side, and is of great thickness (175 feet), it could only have accumulated during a subsidence of the land.

The post-volcanic portion of the delta which reposes upon the lava sheet appears to differ somewhat from that portion which is pre-volcanic, in that it is more of an incoherent gravelly conglomerate, showing, so far as can be discovered, no bedded structure. It has at present a maximum thickness above the lava sheet of about 120 feet. The crest of the delta as left by erosion is a short, nearly level-topped ridge, which not improbably closely corresponds to the original surface. The situation of this upper, or post-volcanic, portion is such that it, also, could only have accumulated during a sinking of the coast. The slopes of the delta are terraced. On the northwest side there is a terrace at 570 feet above tide, and on the side overlooking San Jose Cañon there is a terrace at 500 feet, while on the northeast side of the hill, just beyond the edge of the delta formation, Pholas borings were observed at an elevation of 470 feet. The terraces could only have been formed at stages of an uplift of the coast subsequent to the depression to which the delta owed its origin.

Putting together the various facts which have thus far been advanced, we seem to have the following sequence of events fairly clearly outlined. It is possible, however, that our interpretation underestimates the complexity of the problem considered. As a starting point, in such a picture as we are able to sketch, it may be affirmed that prior to the subsidence which caused the accumulation of a heavy delta in the old valley of the San Jose there had been a prolonged post-Miocene period of uplift and erosion, which gave to the country the main features of the sculpture it now exhibits. This is established by the fact that the delta in its outer portion spreads down over a steep antecedent slope worn partly out of the Santa Lucia granite and partly out of the Monterey shale, and by the fact that a mile and more up the valley of the San Jose, where there are high walls of rock on either side, the delta reposes upon a wide stream-trench floor. At the point examined this trench floor is now 265 feet above the sea, but if the land were now depressed till it stood at sea level, the valley of the San Jose would still be an imposing feature of the topography. Such a feature it must have been before our delta began to accumulate.

This early uplift, which gave rise to the main topographic features

of the country, may have been the same as the great post-Miocene uplift which has been so fully recognized by Whitney, Becker, Le Conte and other earlier investigators. What the character of that uplift was in detail we have no means of saying. Whether it was a uniform, slow uplift, or a rapid and violent one, intermittent in rate of movement, or whether it was a vacillating movement, uplift alternating with temporary depression, we have discovered no evidence to enable us to say. But this fact may be affirmed, that when the uplift reached such a point that the land was about 265 feet lower than now, there was a halt, and the relations of sea and land remained stationary for a time. The duration of this time is measured by the work done by the San Jose in corrading its cañon walls till it had established a flat trench floor of granite. Then the coast began to sink, and the stream detritus, coming from the high-grade cañons in the Santa Lucia, began to accumulate on the floor of the trench, and the delta, which was formerly at the mouth of the stream, began to extend up the valley. The process of subsidence and accumulation continued till the trench floor was buried beneath at least 175 feet of gravel. At this stage of the subsidence the delta was wholly or partially overwhelmed by a flow of lava (carmeloïte). The same flow also mantled the granite slopes above the surface of the delta. The fact that a portion of these granite slopes is flat and terrace-like suggests that it had formerly been terraced by the sea, probably during the earlier uplift of the coast. After the outflow of lava the subsidence continued; and, as this subsidence as yet had little retarding effect upon the action of the streams in the high-grade cañons which drained from the lofty ridges of the Santa Lucia, accumulation proceeded as before, and the delta was built up upon the surface of the lava sheet, and spread out over its edge. This continued till the coast was depressed to at least 620 feet lower than at present. During the accumulation of the delta the subsidence was probably gradual and uniform in rate. In the vicinity of the mouth of San Jose Cañon no evidence of further depression was observed; but our 800 feet sea beach on Huckleberry Hill is only four and one-half miles distant to the northwest, and it seems fair to suppose that the depression which this implies was reached by a continuation of the same downward

movement as that recorded at San Jose Creek. If, on further investigation of the region, it be found that our failure to observe strand lines between the 620 feet level and 800 feet be due to the absence of such features, there would be some warrant for supposing that the drop of the coast through this interval was more rapid than that which preceded it. It may be of service to future observers to state that no search was made for evidence of strand lines in this interval, the 800 feet beach having been discovered at the last stage of our investigations, no time remaining for reëxamination of the field. The depression may possibly have been greater than that indicated by the 800 feet beach, but we have as yet no evidence on this point.

Terraces of the Uplift.—Since the formation of this beach on Huckleberry Hill there has been a progressive uplift of the coast by stages, represented by wave-wrought and stream-cut terraces. The highest of these terraces is one of those mentioned as observed on the slopes of the ancient delta of the San Jose, at an altitude of 570 feet. Corresponding to this in elevation there is a very distinct terrace, strewn with loose and cemented beach material, gravel and bowlders, on the main coast road, near the point where the branch road turns in westward to the new settlement called Carmel City. The terrace is carved out of the Monterey shale, and the cemented shore drift yet remains in place at an altitude of 565 feet. Corresponding to the same horizon, also, are numerous Pholas borings on the seventeen-mile pleasure drive, near the wind gap on the main road, at an elevation of from 540 to 560 feet. From this strand line down to the present sea-shore terraces of various degrees of distinctness become numerous as we descend the slope. They are mostly strewn with bowlders and pebbles, more or less cemented together, and in several cases the adjoining rock surfaces show mollusc borings.

One of the most pronounced of these terraces is observable on the main coast road descending to Carmelo from the wind gap. It has an elevation of from 460 to 480 feet at its rear, and is mantled with the usual thin covering of terrace formations, more or less firmly cemented. Corresponding to this in elevation are the Pholas borings in the Monterey shale at the wind gap between the cañon

of the San Jose and the valley of Carmelo River, at an elevation of 470 feet. These borings are only about ten or twenty feet above the base of the steep revetment which terminates (just within the limits of our map) the ridge which separates the Carmelo from the San Jose. This steep hill, thus squarely truncating the ridge, is, therefore, with little question, to be interpreted as a sea cliff. The steepness and sharpness of the cliff evidence how little the insoluble Monterey shale has yielded to atmospheric erosion since this strand was abandoned by the sea.

Another very well-defined shore line is about 300 feet above tide. This also may be seen in the form of a terrace cut out of Monterey shale on the main road descending to Carmelo Bay. The terrace is, as in the last case, covered with a thin formation of cemented bowlders and pebbles, with some coarse sandstone. The water courses have in many places cut through the terrace formation, and show it reposing upon the worn edges of the inclined Monterey shale. In this, as in all the other terrace formations, fragments of this shale abound. The same strand is represented on the Monterey side of the wind gap, on the coast road, by very abundant borings at an altitude of 300 feet. Borings are also well shown on the same part of the road at about 200 feet. Another very well-marked strand, both on the slopes of Monterey and those of Carmelo Bay, has an elevation of 150 to 160 feet. Below this are various, more or less distinct evidences of former shore lines, but the only set of these which can be signalized as very well defined and persistent is that at from twenty-five to thirty feet above tide. At this altitude are broad wave-cut terraces and stream terraces, which seem to mark a prolonged constancy of the relation of sea and land. On Carmelo Point there is also a terrace fairly well defined at about fifty feet above the tide.

As the uplift of the coast proceeded, the streams purged their valleys of delta material, and lowered their trenches into the underlying rock. In this process they did not always recover their old trenches. This was the case with the San Jose. We have seen that after its old trench was choked with the accumulating delta it was at its lower part covered with a lava sheet. This obstruction seems to have prevented the stream from resuming its old-time

trench in the last mile of its course as the land rose. When the uplift brought this volcanic mass within the range of stream action, the stream was deflected by the obstruction to the south, and took a course between the lava and the Santa Lucia Mountain. Here it began to sink a new trench in the granite; and, although it has succeeded in cutting out a gorge nearly 500 feet lower than the level at which it began operations, the work is incomplete and the stream is still cutting down into the granite. This 500-feet gorge is our best measure of the time which it has taken for the coast to rise through the corresponding interval.

The Carmelo River seems to have recovered and maintained its old trench during the uplift.

The Present Strand.—The present shore features are strongly marked. The height of the sea cliffs of the present strand indicates a broad wave-cut terrace, and at low tide a considerable portion of this terrace is revealed to observation. The vigor with which the sea is encroaching on the land by the recession of the sea cliffs is evidenced by the fact that along the coast, not far south of Carmelo Bay, the slopes which once served for the habitations of the Indians have been encroached upon and removed to the extent of hundreds of yards; and upon some of the isolated stacks and islets lying off the coast, and now utterly inaccessible, save to the seabirds, may be seen the thick layer of black loam, full of abalone shells, which everywhere marks the former occupation of the coast by these people. Notwithstanding the vigor of the action of the sea in causing the recession of the cliffs, it is evident that it must have taken several centuries to have effected the development of the shore features of the present strand. The breadth of the subaqueous shelf, or wave-cut terrace of the present strand, out to a depth of six feet below mean low tide (mean of the lower low waters), has been determined by the U. S. Coast and Geodetic Survey at numerous points along the shore from Pescadero Point to Point Pinos, and is indicated on their chart (scale $\frac{1}{12000}$) by a partial one-fathom submarine contour. A series of measurements made upon the chart show that the breadth of this terrace, from the base of the sea cliff (high-water mark) out to the depth of a fathom, is on an average one-seventh of one mile. The terrace is cut in granite, which is not noticeably de-

cayed or rotton. The stretch of shore here cited is very exposed, and wave action is vigorous continuously. There are no streams yielding detritus which might be used by the waves in the battery process. In this feature of the present strand, then, we have good evidence of the duration for several centuries past of a practically constant relation of sea and land as they now are. How many centuries have been required to carve out of the coastal slope a terrace one-seventh of a mile wide, it is difficult even to guess, so little do we know of the rate of the action. But it has nearly all been done since the occupancy of the coast by the Indians, if we are to judge by the layer of refuse shells which they have left on the White Rocks (stacks) at Point Pinos.

Interesting results might be obtained as to the relative duration of the present strand, and that next above it, at about 25 or 30 feet, by a critical measurement of the width of the latter from the base of its cliffs out to a depth of six feet below its low tide. If one may form a judgment without such critical measurements, the two terraces do not differ greatly, and, being developed under similar conditions, probably represent equal durations of wave action.

Inter-terrace Disturbances.—That certain local movements have affected some of the older terrace formations before the accumulation of the later formations is evidenced in a number of ways. None of these disturbances appear to be of more than minor importance. The earliest evidence of disturbance is that which is suggested by the dip of the beds of the pre-volcanic portion of the ancient delta of the San Jose. These are slightly coherent conglomeritic sandstones, dipping seaward at an angle of about 30°, and locally the sheet of lava which reposes on these sandstones has the same dip. The dip is believed to be greater than the angle of repose of deposits upon the edge of a delta. The disturbance does not appear to affect the post-volcanic portion of the delta, though this cannot be certainly affirmed; it certainly does not affect the terraces which have been scored on its slopes. It is therefore probable that the disturbance took place shortly after the extravasation and consolidation of the lava sheet.

The second evidence of disturbance has already been alluded to. In the ravine traversed by the seventeen-mile pleasure drive, the

terrace formations, which correspond in altitude to the 300 feet terrace, repose upon the carmeloïte lava sheet, and both have been faulted to an extent of at least 20 feet, as is illustrated in Fig. 3.

A third class of facts, which point to local bending of the strata between the deposition of the earlier and later terrace formations, is well exhibited on the low sea cliffs which back the sand beach about half a mile to the west-northwest of the Carmelo Mission. Here there are seen in the cliff sections two sets of strata, both ascribable to the terrace formations, in unconformable relation. This relation is best seen in the cliffs a few hundred yards north of Abalone Point. Here there is a vertical exposure of 20 feet. The lower half of this section is occupied by rather coarse, unevenly bedded, and little coherent sandstones, with a sparing number of pebbles, which have, with little question, been deposited at some little distance off shore, as the equivalent of the coarse, pebbly beach formations of some of the higher terraces. These sandstones have now a southerly dip of 15°, and their upturned edges are truncated to a horizontal plane, showing a very fine base-leveled effect. Upon these truncated edges repose in horizontal attitude the terrace formations of the newer and lower 30-feet terrace, to a thickness of 10 feet. These are loose, sandy formations, with many pebbles.

The same relation is evidenced a few hundred yards still farther north along the shore, where the lower formations are represented by 10 feet of soft sandstone in four distinct beds of about equal thickness. Those beds have a southerly dip of 10°, and their edges have also been truncated to a base level of erosion (wave action) before the deposition upon them of sands and gravels of the 30-feet terrace. The truncation of these gently bowed strata evidently took place when the rate of uplift exceeded the rate of accumulation of the shore drift in the bay, the 30-feet terrace being here an embankment of drift which was carried into the bay and lodged there, rendering it shallow.

Age of the Terrace Formations.—If we assume the earlier uplift, which gave to the coast the larger features of its topography, to be the great post-Miocene uplift which affected the whole coast, then it is evident that we have here a record of events covering both Pliocene and Quaternary time. This we believe to be the case.

There is no record anywhere on this part of the coast of formations which can be referred to the Pliocene other than those of the deltas and terraces. No criteria have as yet been established for discriminating between the Pliocene and the Quaternary in the coast ranges other than palæontological. Palæontological (invertebrate) criteria are unfortunately of little value for a discrimination between rocks of such recent geological age. It is believed that a physical distinction of some importance can be made between two sets of geological conditions comparable to those of the Pliocene and Quaternary respectively. This physical distinction may be expressed in the form of an hypothesis, subject to future scrutiny, to the effect *that the Pliocene corresponds to the period of more or less continuous depression of the coast, till the land was at least 800 feet lower than at present; and that the Quaternary corresponds to the more or less continuous uplift which has affected the coast since the maximum depression was reached.* On this hypothesis the ancient delta of the San Jose is a Pliocene formation and is to be correlated with the Pliocene formations, also clearly of delta origin, which are so largely developed a little to the south of the city of San Francisco. And the terraces of the coast, having been developed during the recent uplift, are of Quaternary age. This hypothesis, it is perhaps needless to remark, is in harmony with the accepted history of events in the Sierra Nevada, even to the Pliocene volcanic activity. The hypothesis implies, moreover, an important interval of high altitude, similar to the present, and of great erosion between the Miocene and the marine Pliocene.

Submarine Valleys.—Our studies of the geology of Carmelo Bay bring us in touch with the question of the submarine valleys of the California coast. These valleys are of peculiar interest, because many of them end abruptly near the shore and have no corresponding rivers on the coast. Notwithstanding the absence of corresponding land valleys, these submarine valleys have been considered to be submerged valleys of stream erosion,* the divorce of the submarine valley from its landward prolongation and the obliteration of the latter being supposed to have been effected by orographic

*See discussion of this subject by Le Conte, Bull. Geol. Soc. Am., 1891, Vol. 2, pp. 323–328.

movements in Quaternary time. The submarine valleys are, moreover, supposed to have been formed in Pliocene times. Our observations at Carmelo Bay do not harmonize with these views. According to the geological record as interpreted by us at Carmelo Bay there is no evidence of an elevation of this part of the coast since Miocene times exceeding the present altitude. The San Jose is actively deepening its trench in granite down close to the present shore. Its ancient gorge was choked with delta material after it had reached a base-level which is now between 200 and 300 feet above the present one. The Carmelo River is at or near base level only in its lower stretches, and the fact that its valley is carved out of soft shale accounts for its apparent maturer condition. The Carmelo, moreover, passes between rocks at its mouth which are only one-eighth of a mile apart, and it is improbable that the rocky trench floor is many feet below the sandy bed of the river. If the land had been higher than at present since Miocene times, we would have had a different topography at the lower parts of these streams. Moreover, if the delta deposits of the San Jose, and the more extensive delta deposits of the San Francisco peninsula, are of Pliocene age, then the Pliocene was a period of depression, the river courses along the coast were choked, and no deep valleys of erosion were formed.

With these objections to the hypothesis that the submarine valleys of the coast are valleys of erosion, it may be asked, Can any other explanation of their origin be offered? To this there is an affirmative answer. Two of these valleys have come under our observation. One of them heads in Carmelo Bay, and has a depth of 135 fathoms within a little more than half a mile from shore. This valley lies in the line of the cañon of San Jose, if we consider for the last mile the old buried cañon, and not the one now occupied by the stream, which is a recently cut trench deflected from the general trend of the old stream. This cañon of the San Jose is straight, and lies along the line of the abutment of the Monterey shales against the bold granite slopes of the Santa Lucia. This line of abutment has the characters of a fault, and was probably established during the post-Miocene uplift. It is, therefore, probable that the submarine valley of Carmelo Bay is structural in its origin, and

represents the continuation seaward of the fault valley in which the San Jose first began to flow.

The other submarine valley to which we refer is that of Monterey Bay. This is one of the largest, most important, and most critical for this discussion along the coast. This, also, seems to be a structural valley, and to occupy a great synclinal trough or depression in the Monterey shale. This formation occupies the coast in the vicinity of Santa Cruz, and it has been examined for many miles along this part of the coast, and found to have a constant southerly or seaward dip at low angles (from 5° to 10°). At the head of the embayment near Pajaro Cañon the same rocks have a westerly dip at somewhat higher angles, and at Monterey, on the south side of the bay, the same formation dips northerly at an average angle ot about 5°. These facts indicate clearly a synclinal structure for the Bay of Monterey. Thus, two of the submarine valleys appear to be structural features, and the others will perhaps also be found to have a similar origin.

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THE SODA-RHYOLITE NORTH OF BERKELEY.*

BY

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CONTENTS.

OCCURRENCE.

The rock which forms the subject of this paper is found on the crest and western slope of a ridge of the Contra Costa hills, which extends northward from Berkeley to near the village of San Pablo. So far as is at present known, its occurrence is limited to a belt about five miles in length and one mile in width. The rock is most abundant in the southern portion of this area, and it there lies well down from the ridge. Further north, where the ridge is lower,

*My acknowledgments are due to Professor A. C. Lawson, with whose advice, and under whose supervision, both the field work and laboratory investigations detailed in this paper have been carried out.

it lies on the upper slopes, and on the crest in the form of small knobs or buttes.

GEOLOGICAL RELATIONS.

As a formation the rock is clearly recognized to be a volcanic flow. It forms a comparatively thin sheet, nowhere over one hundred feet in thickness, and generally considerably less, spread out on an unevenly eroded surface. Since its extravasation it has been depressed and buried by later sediments, and the whole again uplifted, tilted, faulted, and eroded.

This erosion has not only removed the greater portion of the mantle of overlying sediments within the area described, but has also dissected the sheet, and carried away very considerable portions of it; so that it is no longer a continuous formation, but merely a succession of patches distributed irregularly on the slope of the ridge. Of the geological continuity of these patches and the essential unity of the formation there can be no reasonable doubt. Our partial knowledge of the underlying and overlying formations does not enable us to fix with precision the age of the extravasation. This much, however, is clear: The sheet lies indifferently upon the eroded surface of the crystalline schists of the Coast Ranges, and upon the aucella-bearing, Knoxville division of the Cretaceous (Neocomian). It is overlaid by strata in which no fossils have yet been found, but which are probably Pliocene. The age of the flow is thus late Cretaceous, or early or middle Tertiary. The extensive erosion of the aucella-bearing sandstones and shales, together with the total absence of the later Cretaceous rocks, indicates that the sheet is probably post-Cretaceous.

GENERAL PETROGRAPHICAL CHARACTER.

The rock composing this formation may be described under three quite distinct types. The first, which will be known as the "porphyritic facies," represents the most advanced stage of crystallization in the flow, and exhibits the features of a quartz-porphyry, viz., a cryptocrystalline ground-mass with quartz and feldspar phenocrysts. The second type presents more the aspect of a rhyolite with the features common to surface volcanic flows, viz., a glassy spherulitic matrix, vesicular structure, and well-marked fluxion lines.

It represents an intermediate stage of crystallization, and will be termed the "spherulitic facies." The third type is a volcanic glass with spherulitic and porphyritic modifications, representing a very slightly differentiated phase of the magma. It will be known as the "glassy facies."

The Porphyritic Facies.—The porphyritic facies is a hard, compact, fresh rock, dull white in color with subconchoidal fracture. Phenocrysts of quartz and feldspar are abundantly disseminated throughout the ground-mass, which is in most cases cryptocrystalline, but occasionally fine granular. Some secondary veins of quartz traverse the rock and the surface is in places stained yellow, or brown by iron oxide.

Under the microscope the ground-mass is seen to be a microgranular aggregate of quartz and feldspar. No glass could be detected. The porphyritic feldspar is cloudy from decomposition products, but retains traces of twinning structure which show it to be a plagioclase. The porphyritic quartz exhibits in a few instances pyramidal terminations, but for the most part has lost its original form by corrosion and resorption by the magma; the intricate bays thus formed are bordered almost continuously by a narrow band of glassy material which merges insensibly into the surrounding granular ground-mass.

Fig. 1, Plate 5, illustrates such a corroded crystal with its glassy border. The quartz contains numerous small inclusions of various, but mostly irregular, shapes, each containing a stationary bubble and arranged in rudely parallel bands. No ferro-magnesian silicates are present.

Fig. 2, Plate 5, represents a typical appearance of this rock as observed between crossed nicols.

The Spherulitic Facies.—The spherulitic facies presents numerous variations in detail of structure, but is in general white or grayish in color, with a mottled aspect, due to the presence of minute black or gray dots; its structure varies from massive to finely laminated or vesicular; its fracture is uneven to lamellar. There are two varieties of this spherulitic facies, a massive and a laminated.

The Massive Spherulitic Variety.—The variety which gave the most definite results under the microscope, and of which a sample

was subjected to chemical analysis, is a compact lithoidal rock, with ill-defined banded structure; the ground-mass is white, but is rendered grayish by crowds of minute dark-colored dots, with numerous phenocrysts of milky white feldspar.

Under the microscope the ground-mass is seen to be largely composed of glass with occasional irregular patches which have become partially devitrified. It is in parts clouded with yellowish iron oxide and contains a few scattered grains of magnetite. Feathery radial aggregates of chalcedony are present in small amount. The minute dots which are scattered irregularly through the matrix are spherulites, exhibiting in greater or less perfection the characteristic black cross between crossed nicols. The spherulites are rarely circular, but have commonly an irregular or wavy outline. Numerous radial cracks divide them, but the highest powers failed to separate the individual fibers, and therefore the mineral character could not be determined. In color they are yellow or brownish; in nearly every case the body of the spherulite is surrounded by a border showing stronger interference, optically continuous with the center, but lighter than it in color, and shading off imperceptibly into the still lighter glass of the ground-mass.

Many of the spherulites have phenocrysts of feldspar at their centers, and nearly all of the larger feldspar phenocrysts are surrounded by groups of spherulites, radiating from points on the edge of the crystal, and so intergrown as to produce a festooned effect.

Fig. 3, Plate 5, illustrates such a crystal with its encircling spherulites.

The feldspar is mostly plagioclase, twinned and sometimes zoned. Orthoclase is also present.

There is a small amount of free quartz in grains and patches, the corroded remains of original idiomorphic forms.

No ferro-magnesian silicates are present.

Fig. 4, Plate 5, illustrates a characteristic aspect of this rock between crossed nicols.

The Laminated Spherulitic Variety.—The most abundant and most noticeable variety of the spherulitic facies is a form which is very distinctly laminated. This rock varies in color from dull white to gray, yellowish, and rarely purplish shades. In the more

perfectly laminated forms the lamellæ are very thin and easily separated. More often they are not readily separable, being defined by color modifications or by the presence or absence of the spherulitic dots. The lamination planes sometimes extend without curvature or interruption over considerable areas, giving rise, in weathered masses of the rock, to sharp, angular forms. More commonly the fluxion lines are extremely contorted, twisted into knots, merged with one another or interrupted by shear planes. In some cases the rock has been completely shattered, the angular fragments having been recemented originally by glass and secondarily by silica into a compact breccia.

This phase of the rock is usually vesicular, the vesicles ranging from minute clustered pores to cavities an inch in diameter, of irregular shape, drawn out in the direction of flow, and lined or rarely filled with iron-stained silica. The flow lines pass around these larger cavities showing that they were formed, not by solution but while the rock was still viscous.

In thin section this variety of the spherulitic facies is found to be composed largely of glass, portions of which have become devitrified. The spherulites are but imperfectly developed, but are arranged in rows or groups along the well-marked flow lines. No phenocrysts were detected in this variety.

Intermediate forms are found between the spherulitic facies and the porphyritic facies, in which the spherulitic structure disappears, the laminated texture and glassy ground-mass still remaining in greater or less proportion.

On the other hand the spherulitic facies passes by less regular gradations into the third form, or glassy facies.

The Glassy Facies.—This facies includes several varieties, of which the simplest is a glass of greenish black color and subconchoidal fracture. Under the microscope it is seen to be a very uniform glass with imperfect perlitic structure. Numerous slender microlites are scattered through the glass without any definite arrangement.

Slightly more differentiated than this glass is a porphyritic form, dark green to light green or gray in color and of a more lithoidal aspect. Under the microscope it is seen to have a glassy ground-

mass with occasional patches of granular material, and numerous phenocrysts of feldspar and grains of magnetite.

A section of this phase is illustrated in Fig. 5, Plate 5.

In places this porphyritic glassy rock is wholly or largely made up of curious spherical masses varying in size from an eighth of an inch up to three inches in diameter. On a weathered surface these spheroids stand out prominently and they may frequently be wholly separated from the surrounding rock. Their surface is rarely smooth, but in the larger ones always more or less knobby or reniform. In some cases two will coalesce, producing a mass shaped like a dumb-bell.

The smaller ones are solid and in section present a radial structure more or less perfect. Those of larger size are nearly all hollow, having a crust of the rock substance and within, a lining of chalcedony, which sometimes fills the whole space or incloses a center of quartz, calcite, or marcasite. A thin section of the rim of one of these hollow spheroids shows it to consist of the same materials as the main mass of the rock, but in a more advanced state of crystallization. The phenocrysts are more abundant and the ground-mass consists of long radial aggregates of fibers grouped about points on the interior surface of the shell, with a small amount of interstitial glass. These fibrous aggregates do not afford a distinct black cross between crossed nichols, but exhibit a very feeble undulatory extinction.

The spheroidal masses are probably of the nature of spherulites, though having some characters not common to such structures.

Distribution of the Different Facies.—The three facies of the rock described in the foregoing pages are very unequal in their relative abundance.

The spherulitic type is the dominant form of the rock, composing not less than two-thirds of the bulk of the sheet. The southern portion of the formation is almost wholly made up of this type, and patches of it are found over the whole area of the sheet.

In the northern portion of the area over which the formation is found the porphyritic type prevails, mingled with more or less of the spherulitic facies.

The glassy facies is confined to one small outcrop in the southern

portion of the sheet, being but a small fraction of the bulk of either of the other types.

Summary of Microscopic Study.—The study of the various facies of rock from different parts of this formation demonstrates that we have here an almost continuous series of increasing crystallographic development, from a simple glass, through microlitic and spherulitic forms to a microgranular porphyry. The mineralogical composition, where minerals have been developed, is uniform and very simple, quartz, orthoclase, and acid plagioclase being the essential constituents, and magnetite the only accessory.

The entire absence of ferro-magnesian silicates is an unvarying characteristic of the rock in all its phases.

The petrographical characters are in harmony with the conclusions arrived at in the field as to the extravasation of the formation as a surface flow.

CHEMICAL CHARACTERS.

The interesting petrographical differentiation of the formation, as revealed by studies in the field and with the microscope, suggested an inquiry as to whether there existed a corresponding variation in the chemical composition. Chemical analysis was also necessary to decide the position of the rock in the accepted scheme of classification, as the microscopic study still left us in doubt as to the dominant alkali.

To this end three analyses were made, one of each type described. The results obtained, together with two other analyses for comparison, are exhibited in the following table:—

	I.	II.	III.	IV.	V.
SiO_2	83.59	75.46	69.85	75.50	77.70
Al_2O_3	5.42	13.18	13.34	13.25	12.30
Fe_2O_3	} Trace	.91	.73	1.02	.60
FeO				.91	.20
CaO	3.44	.95	.87	.90	.20
MgO	Trace	.10	Trace	.07	.70
K_2O	1.37	1.09	2.68	2.85	.20
Na_2O	5.33	6.88	5.58	4.76	7.00
H_2O	.76	.93	6.15	.41	.50
	99.91	99.50	99.20	100.05	99.40
Sp. g.	2.54	2.42	2.32		2.63

I. Porphyritic facies, Berkeley; analyst, C. Palache.

II. Spherulitic facies, porphyritic variety, Berkeley; analyst, C. Palache.

III. Glassy facies, porphyritic variety, Berkeley; analyst, C. Palache.

IV. Lithoidal rhyolite,* Yellowstone National Park.

V. Quartz-keratophyre,† Mt. Elizabeth, Australia, Howitt.

An inspection of the three analyses of the Berkeley rock shows that its different facies are not identical in composition. The silica content varies in a pronounced way, and presents a gradation decreasing with the grade of crystallization. The specific gravity, also, decreases in value with the decrease in silica, a fact contrary to the general rule.

The explanation of this anomalous variation of the density of the rock is doubtless to be found in the increase in the proportion of glass (fused quartz, resolidifying as glass, being lighter than crystalline quartz‡), and in the fact that the glassy rock is rich in water.

The porphyritic rock contains more lime than the other two facies, and also differs from them in the small proportion of alumina which it contains, the amount being less than would be expected from the amount of alkalies and lime, with which it is presumably combined in the form of a silicate.

The variation in the silica content is interesting and suggestive, and seems to be an illustration of the operation of Soret's principle, now generally accepted in discussions§ on petrogenesis.

Those portions of the rock which are holocrystalline, and which, therefore, have presumably solidified most slowly, are richest in silica, while the glassy facies which solidified rapidly is most basic.

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*J. P. Iddings, Origin of Igneous Rocks, Bull. Phil. Soc. of Wash., Vol. XII, June, 1892, p. 203, Table I, analysis 26.

† H. Rosenbusch, Ueber die chemischen Bezühungen der Eruptivgesteine. Mineralog. und Petrog. Mitth Vol. XI, 1889, p. 177, Table I, analysis XX.

‡ Teall, J. J. H , British Petrography, 1888, p. 12.

§ Teall, J. J. H., The Sequence of Plutonic Rocks, Natural Science, Vol. I, June, 1892, pp. 288–300.

Iddings, J. P., The Origin of Igneous Rocks, Bull. Phil. Soc. Wash., Vol. XII, pp. 89–214, June, 1892.

But while the three facies of the rock exhibit a pronounced differentiation as regards their acidity, they have some strongly marked features in common. In all these types iron is present only to the extent of a fraction of one per cent., and is probably represented mineralogically entirely by the minute granules of magnetite seen in the slides.

Magnesia is found only in traces, as was to be inferred from the absence of ferro-magnesian silicates. The important chemical feature, however, which the three facies have in common, is the ratio of the alkalies. In each facies the soda greatly preponderates over the potash.

NOMENCLATURE.

The latter fact, taken together with the known presence of acid plagioclase in addition to the orthoclase, supplies us with all the information necessary for locating the rock definitely in the classificatory scheme.

But here we are met by the natural difficulty that a name applied to any one of the three facies is not strictly applicable to the other two. Thus the porphyritic facies approaches in its characters a soda-rich quartz-porphyry, or quartz-keratophyre. The spherulitic facies, considered by itself, is a soda-rhyolite, and the glassy facies is often an obsidian. Yet the three facies are clearly a geological unit, and in general discussions must be referred to by a single name. The intermediate facies, as the most abundant form, is therefore taken as representative of the essential features of the formation, and the rock as a whole is designated a soda-rhyolite.

A comparison of the analyses of the Berkeley rocks with those of soda-rhyolite and quartz-keratophyre given in the table, shows that the nomenclature adopted is justified by the composition of the various facies.

OTHER OCCURRENCES.

Volcanic rocks of the acid rhyolitic type have been hitherto reported from but one locality in the Coast Ranges, a dyke of rhyolite near the New Almaden mine, Santa Clara County, described by Dr. G. F. Becker.* This dyke he regards as certainly post-

*Quicksilver Deposits of the Pacific Coast, Monograph XIII, U. S. G. S., pp. 123 and 313.

Miocene, and probably of late Pliocene age. No analyses are given.

The comparative rarity of the type to which they belong gives interest to the soda-rhyolites north of Berkeley. In this connection it is worthy of note that the crystalline schists found underlying this formation at Berkeley are characterized by the occurrence of minerals rich in soda, notably glaucophane, albite, and paragonite. It is hoped that further study may throw more light on the relations of the soda-rhyolite, both to these schists and to the other volcanic rocks of this area, both of earlier and of later age.

EXPLANATION OF PLATE 5.

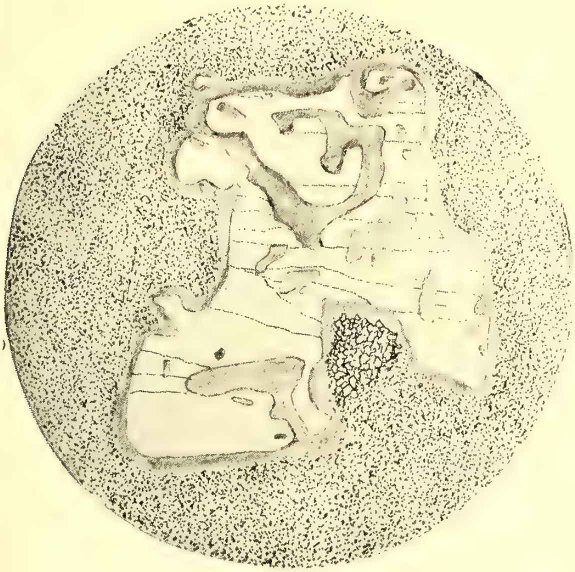
FIGURE 1.—Corroded quartz phenocryst with glassy border. × 30.

FIGURE 2.—Illustrating porphyritic facies with microcrystalline ground-mass; *q*, quartz; *f*, plagioclase. × 30.

FIGURE 3.—Plagioclase phenocryst with border of spherulites in glassy ground-mass. Nicols +, × 30.

FIGURE 4.—Characteristic section of soda-rhyolite. Nicols +. *q*, quartz; *f*, plagioclase. × 30.

FIGURE 5.—Rhyolite glass with phenocrysts. Nicols +. *q*, quartz; *f*, feldspar. × 30.



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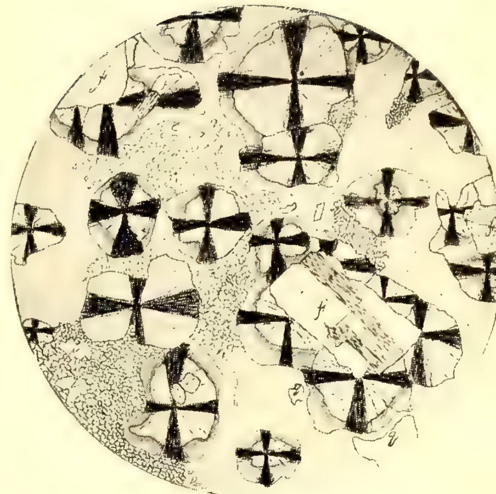

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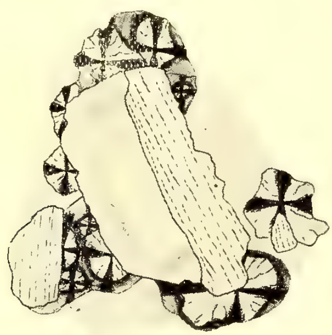

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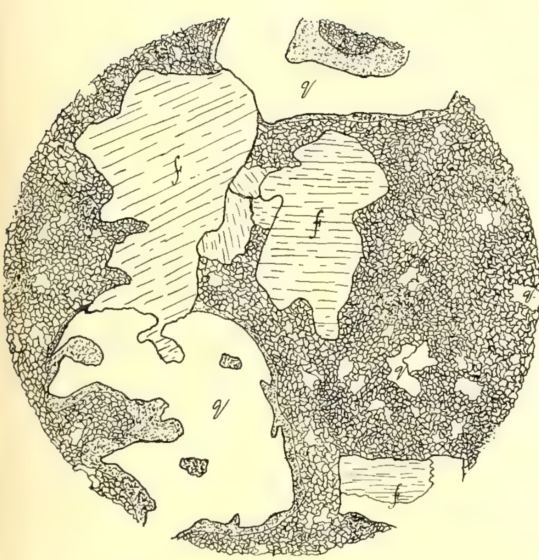

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UNIVERSITY OF CALIFORNIA.
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Vol. 1, No. 3, pp. 71-114, Pls. 6-7. ANDREW C. LAWSON, Editor.

THE ERUPTIVE ROCKS OF POINT BONITA.

BY

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CONTENTS.

INTRODUCTION.

Point Bonita forms the southern extremity of Marin County, California, being the most westerly headland on the north shore of the entrance to San Francisco Bay. In passing out through the Golden Gate, the coast-line is here seen to turn abruptly to the north, and it is along this stretch of shore for a distance, in a straight line, of about four-fifths of a mile, that the rocks to be described are mainly exposed. This portion of the coast has been eroded by the waves of the Pacific into precipitous cliffs, loftiest at the point indicated on the map as the site of the old tower, diminishing in height towards the north, and ceasing at the sand-bar, which, in ordinary weather, separates the waters of the ocean from

the little sheet known as Rodeo Lagoon. In places, the cliff has retreated inland, past the original crest of the hill from which it has been cut, and is thus diminishing in height with its recession. That the land is being encroached upon by the sea with geologic rapidity, is thrust upon the attention in many ways, and is particularly noticeable along the line of high cliffs extending from the rocky islet on the western edge of the map, southward to the lighthouse. The indications of rapid waste may be seen in the abruptness and steepness of the declivities, in the bareness of the rock surfaces, in the occurrence of overhanging masses threatening to fall at any moment, in the evidence of recent sliding, and lastly, in the absence of any considerable amount of beach accumulation. Even in calm weather, the long heavy swell breaks with great force at the base of the cliffs, and there are places under the rock upon which the fog siren stands, where the concussion of a wave on the west, is seen to be followed by a hissing jet of spray, issuing from the opposite or lee side, showing a complete undermining of the mass at that point. It is impossible to say to what distance out to sea the western slope of the hill upon which the old tower stands once extended, but from the contour of the ground it could hardly have been less than half a mile, and was probably more.

Although the sea has thus cut into the hills and provided good sections of the volcanic rocks, yet the exposures as a whole cannot be regarded as entirely satisfactory, as for more than half the distance, the cliffs are not accessible by ordinary means, and have little or no beach below them. On the land side still more unfavorable conditions prevail, for the hills are heavily covered with a sandy loam, and the contact between the eruptive rock and the sedimentary formations lying to the east, is visible only for very short distances at a few isolated points. Owing to these unfavorable conditions, it has not been possible to formulate any statement of the mutual relations of all the rocks included in the area which could be accepted as complete, yet some important facts bearing upon these relations may be presented with confidence, and the study of the geology of the surrounding region may be expected to throw light upon such points as are obscure in the very limited area under discussion.

GENERAL ACCOUNT OF THE GEOLOGY.

Reference to the accompanying map will show the general distribution of the several rocks. It will be seen that a considerable portion of the area is covered by comparatively recent deposits, represented by dotting, and the mapping of the underlying formations must be taken as more or less conjectural when so concealed. The eruptives, with the two small patches of pyroclastic rock, form the mass of Point Bonita proper, and extend in an almost unbroken belt of varying width up to the sand-bar at the lagoon. Immediately to the east occurs sandstone, which is identical with that so extensively developed on the San Francisco Peninsula and about the shores of San Francisco Bay. Although generally regarded as of Cretaceous age, its true position cannot be considered as finally settled, and it will therefore be spoken of as the San Francisco sandstone, in accordance with the usage of Blake.* At the point marked G, the sandstone is distinctly bedded, and dips north 25° east, at an angle of 55°. The contact is defined by a little ravine, but the actual junction of the two rocks is concealed. Farther north, near C and D, two small patches of the sandstone are seen resting upon the eruptive rock, the latter being intrusive.

Succeeding the sandstone on the north and northeast occurs a band of the very characteristic dark-red bedded jaspers described by Blake,† Newberry,‡ Whitney,§ and Becker,|| and named "phthanites" by the latter. The eruptive rock has been intruded into these jaspers, and they are disposed in great confusion along the upper portions of the cliffs, with a general tilting to the east. Where less disturbed their dip is such as would indicate that they pass under the sandstone to the southwest. Sandstone again occurs in the northeast corner of the map, and, although not sufficiently

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*Reports of Explorations and Surveys for a Railroad from the Mississippi River to the Pacific Ocean, Vol. V, House of Rep., 33d Congress, 2d session, Ex. Doc. No. 91, Geol. Report by W. P. Blake, pp. 145–154, Washington, 1856.

† *Loc. cit.*, pp. 155, 156.

‡ Report of Explorations, etc., Vol. VI, Senate, 33d Congress, 2d session, Ex. Doc. No. 78, Geol. Report by J. S. Newberry, p. 12, Wash., 1857.

§ Geological Survey of California, Geology, Vol. I, p. 82, 1865.

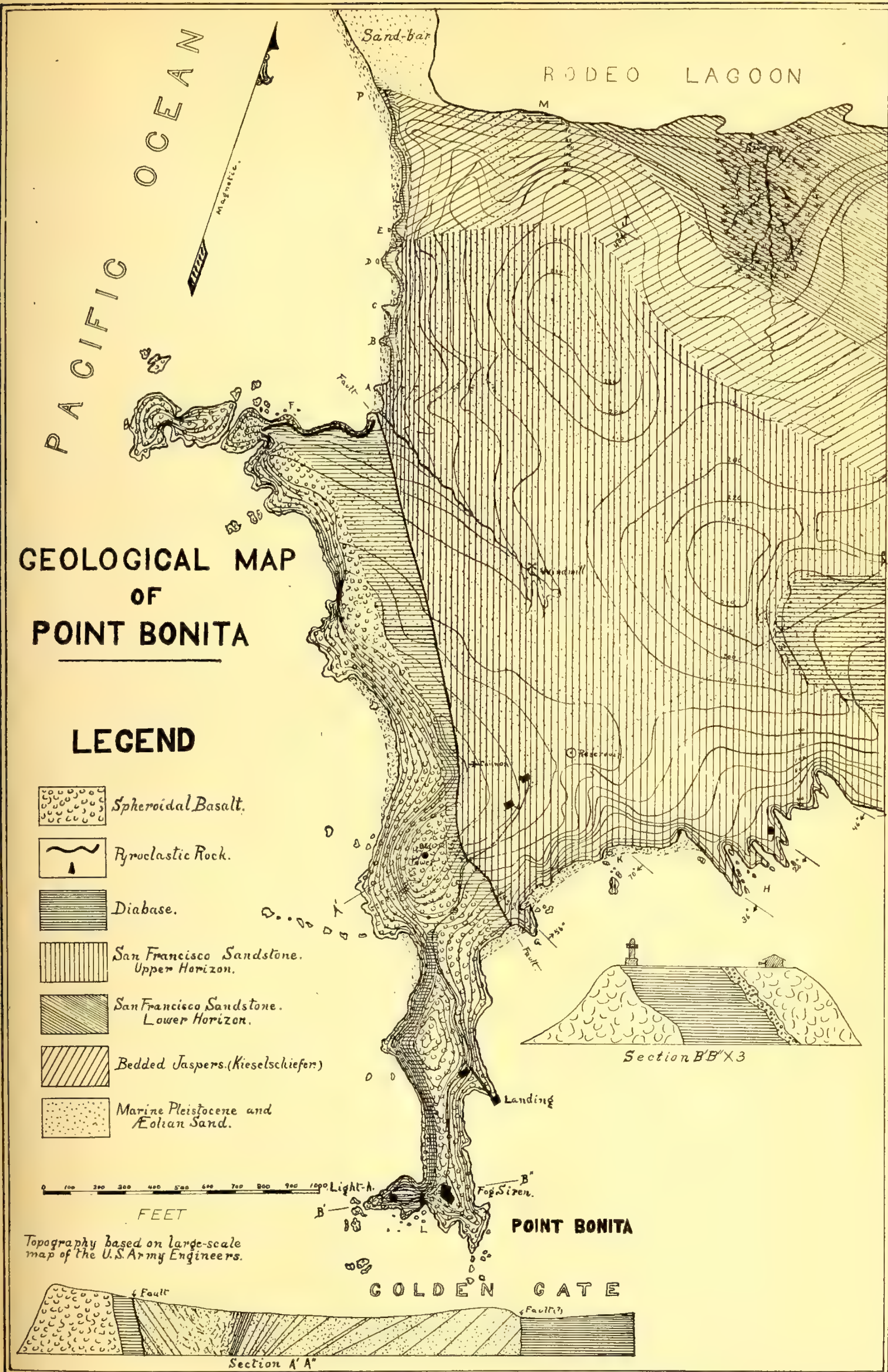
|| Quicksilver Deposits of the Pacific Slope, Monog. XIII, U. S. Geol. Surv., pp. 105–108.

exposed to afford observations for dip and strike, would seem to underlie the jaspers, and to belong to a lower horizon than the sandstone previously referred to.

After the area had had substantially its present topographical features impressed upon it, it was submerged, and covered with a deposit, of which vestiges remain up to the summit of the hill upon which the old tower stands, now 280 feet above the sea. This deposit is most conspicuously shown just south of the stream mouth, at A, where it forms a nearly vertical bluff, more than 100 feet in height, of horizontally stratified material, only partially consolidated. At the base of the bluff this consists of pebbles of volcanic rock and jasper, while the highest portions of the formation are composed of a clayey sand, which readily disintegrates into a loose sandy loam.

It has been said that a portion of the eruptive rock is intrusive into the overlying sedimentary formations; with this rock, however, are associated other rocks, which are certainly not intrusive, but which possess, on the contrary, all the features which are generally accepted as characterizing lavas extravasated upon the surface. The most typical facies of the two rocks may be readily distinguished in the field, the one being compact and amygdaloidal, showing no crystals to the unaided eye, and possessing a very marked spheroidal structure, the other being a distinctly crystalline rock of almost gabbroitic aspect, traversed by irregular joint planes, and without spheroidal structure. The latter rock does not, however, always preserve its distinctive character, and may be traced, both in the field and in the microscopic slides, into modifications not distinguishable with absolute certainty from the typical spheroidal rock. The chemical analyses show that both rocks are probably derived from the same basic magma.

The problem thus presented for solution requires that the eruptive terrane be differentiated throughout into the two formations which are clearly shown in certain places; that the relations of the two divisions to each other, and to the sedimentary series, be unraveled; and that some explanation be offered for the various structural peculiarities of the eruptive rocks presently to be described.


GEOLOGICAL MAP OF POINT BONITA
PACIFIC OCEAN
RODEO LAGOON
Sand-bar
Magnetic
Fault
Windmill
Reservoir
Landing
Light-H.
Fog Siren.
POINT BONITA
GOLDEN GATE
LEGEND
Spheroidal Basalt.
Pyroclastic Rock.
Diabase.
San Francisco Sandstone. Upper Horizon.
San Francisco Sandstone. Lower Horizon.
Bedded Jaspers. (Kieselschiefer)
Marine Pleistocene and Æolian Sand.
FEET
Topography based on large-scale map of the U.S. Army Engineers.
Section B'B" X 3
Section A' A"

THE SPHEROIDAL* BASALT.

The eruptive rocks admit of a threefold division,—the spheroidal basalt, the diabase, and the associated pyroclastic rocks. These will be described in the order named. The difficulty experienced in defining with precision the boundary between the first two rocks, led to the collection of a rather numerous suite of specimens, considering the smallness of the area, and the preparation of about sixty microscopic slides, thus affording sufficient material for a full petrographical description.

Occurrence and Structural Peculiarities.—Immediately south of the narrow neck of rock joining the fog signal and lighthouse, and close to the latter, a rocky mass juts into the ocean, and is connected with the cliff, some fifty feet down, by a natural bridge of rock. Its appearance, seen from a position west of the lighthouse, is well represented in Plate 7, Fig. 1, and the illustration shows very strikingly one phase of the remarkable structure which characterizes the spheroidal basalt, and suggests its name. Upon clambering down to the rock, it is seen that the curved figures shown in the illustration are the transverse sections of elongated, bolster-like, or bale-like masses, whose longer axes are in general roughly parallel and extend downwards and away from the observer, that is, dip in an easterly direction. An examination of the cross sections of these bales shows that their material is not quite uniform, they frequently exhibiting a tendency to weather out near the center, leaving a surrounding shell, as may be seen in the upper left-hand corner of the figure; moreover, although the whole rock is full of amygdules of dark green color, these seem larger, and more numerous, in the interior portions of each bale, and particularly near the weathered inside surface of the surrounding shell. The masses are also much fractured transversely, each crack being usually accompanied by miniature faulting. Some amygdules were observed filling greatly elongated vesicles.

Upon looking back at the cliff, the line of contact between the

*The adjective "spheroidal" is used throughout this paper in deference to previous usage only; for, as will appear in the sequel, the forms assumed by the basalt can seldom properly be called spheroids.

spheroidal basalt and the diabase to the east, is seen to rise from the water's edge, pass immediately to the right of the natural bridge, and run up to the top of the cliff at a point a little west of the lighthouse. The line is quite sharp, and the difference of character in the two rocks, thus placed in juxtaposition, very striking; but the sea and weather have transformed the junction into a more or less open cleft, and it is impossible to say whether it is a line of faulting, or a true igneous contact. A few steps to the east, spheroidal basalt again occurs, and at the southeast extremity of the point may be seen a structure less striking, but similar to that just described.

Leading from the fog siren to the keeper's house, a path has been cut in the rock, and affords opportunity for examining the structure of the point on the east side. Just behind the store shed at the head of the landing stairs, the cutting exposes the sectional forms shown in Fig. 1. The sections are traversed by a number of

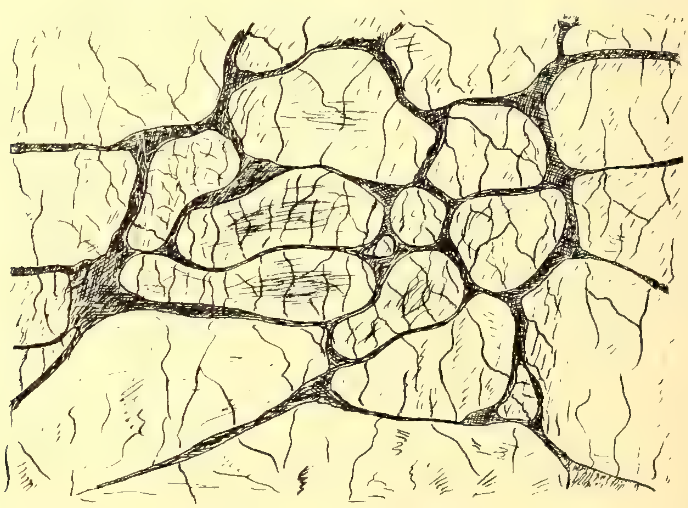


Figure 1.—Section of spheroids beside the path, near storehouse of the fog signal station.

cracks, it being generally possible to discern something like regularity in the way in which those transverse to the longer axes of

the ellipsoidal forms predominate. Upon descending the steps to the landing, the spheroidal rock may be seen continuing down to the water, and showing conspicuous spheroidal forms on the wave-washed surfaces. A notable feature of the rock at this place, and for some two hundred yards northward, is the abundance of included fragments of unmistakable red jasper. Such pieces seem to have suffered little alteration beyond having their usual dark red or chocolate color changed to a bright vermilion—a change which was constantly observed wherever such included fragments were found.

About one hundred yards directly south from the old tower, the path makes an abrupt turn to the east, after running for a few paces along a very narrow ridge of rock. On the steep slope just above and to the north of the turn, occur the curious spheroidal masses shown in Plate 7, Fig. 2. As the illustration shows, they are of various sizes up to three feet in diameter, and appear to be imbedded in a shattered mass of rock similar to that of which they are formed. The view shown unfortunately affords only one aspect of these masses, making it appear that they are really spherical in form; but upon going around to the ground in the left of the illustration, it is at once evident that these bodies are not true spheroids. The one depicted is seen to be lying upon a similar rounded mass underneath, and to present the appearance shown in Fig. 2, as though it

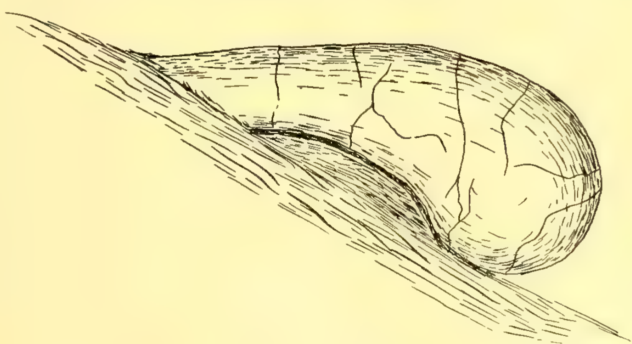


FIGURE 2.—Side view of large spheroid shown in Pl. 7, Fig. 2.

had been laid there in a pasty or viscous state, and had assumed its

present shape under the influence of gravity. A certain amount of crushed and sheared material fills the interstices between the spheroids, and seems to be made up of comminuted fragments of the same rock. It is, however, too crumbling and too full of secondary products for a satisfactory determination. The rock of these spheroids has a pronounced porphyritic texture,—the crystals of feldspar varying from those of small dimensions up to those of about 15 mm. in length, and standing out conspicuously on the weathered surface as light-colored spots. The mass shown in the illustration was drilled and split open, but the interior showed no perceptible difference, either in structure or texture, from the exterior surface, and was traversed by irregular joint planes.

Upon descending the steep talus-slope to the strip of beach to the west of the spheroidal masses, the contact can be made out between the spheroidal basalt and the diabase; the latter appears to be intrusive, and includes, near the contact, a few of the characteristic rounded forms of the basalt. At the southern end of the beach the peculiar spheroidal structure is very conspicuously shown. The forms are here lenticular, rather than spherical, as may be seen from the large detached masses, three to five feet in diameter, newly fallen from the cliff. The rock has been minutely fractured in an astonishing manner, and in places is a mere mass of brittle fragments, slightly recemented together. The spheroidal structure is also exhibited at the northern end of the beach, where the rock is excessively shattered, and filled with veins and stringers of calcite. On the way down to the beach, and within a few feet from the top of the slope, a block of sandstone about four feet in diameter was observed resting partly imbedded in the volcanic rock.

The spheroidal basalt may again be closely examined, along the beach northwest of the old tower, but presents no new features. From this beach northward, the cliffs are inaccessible until the low land at the stream mouth is reached. The position occupied by the spheroidal basalt at F, is represented somewhat diagrammatically in Fig. 3. The portion shown on the left of the sketch forms a low, wave-washed projection, with smooth, water-worn surfaces, showing very conspicuously the structural peculiarity which is so characteristic of this rock. It is evident that the mass is not a homo-

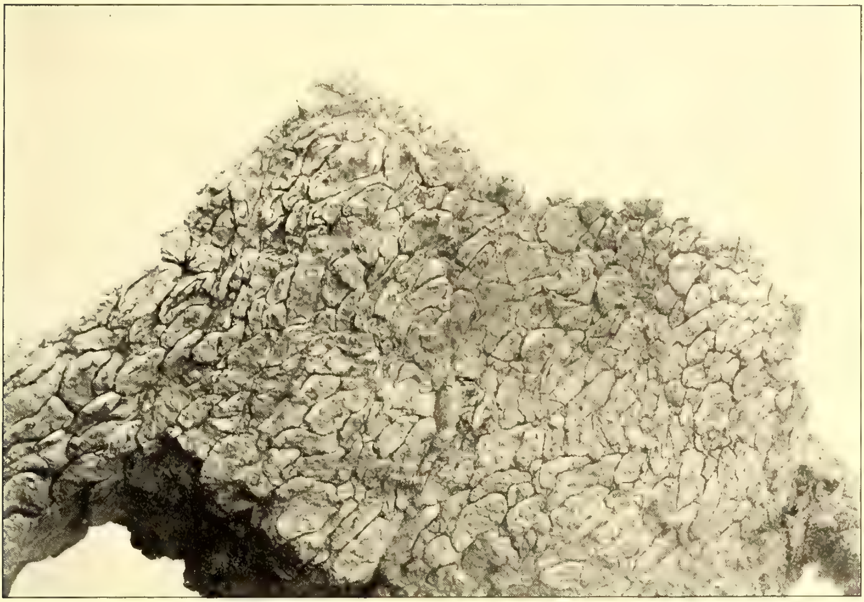


FIGURE I.—JOINT SURFACE OF SPHEROIDAL BASALT NEAR THE LIGHTHOUSE, SHOWING THE CROSS SECTIONS OF THE LONG, CLOSELY-FITTING BALES, WHICH EXTEND DOWNWARDS AND AWAY FROM THE OBSERVER.

FIGURE 2.—LARGE SPHEROIDS AT THE TURN OF THE PATH, 100 YARDS SOUTH OF THE OLD TOWER.

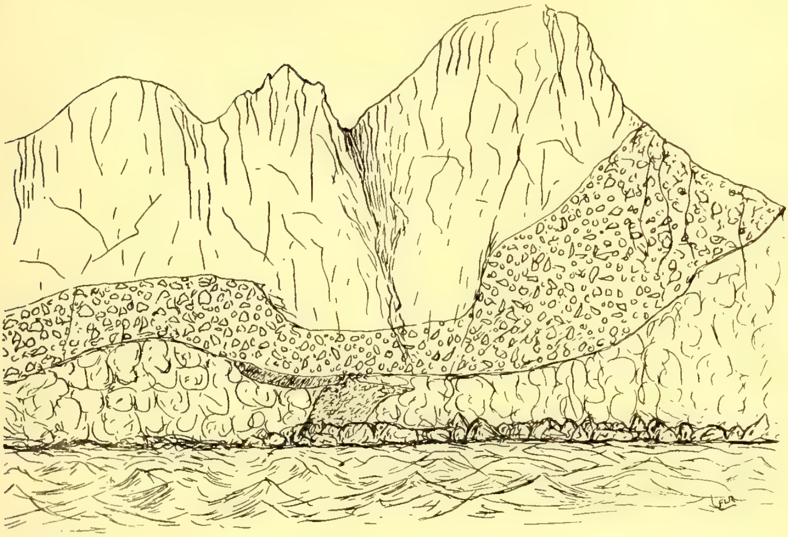


FIGURE 3.—Diagrammatic sketch of cliff at F, showing spheroidal basalt overlain by pyroclastic rock. The upper portion of the cliff is diabase, which can also be seen intrusive into the basalt below.

geneous solid, but is composed of separate, closely-fitting bodies, of various sizes, up to about two feet in diameter, and of such shapes that their sections show circular, elliptical, and other less regular forms, bounded by closed curves. The bounding surfaces are perfectly sharp and definite, and entirely inclose each separate spheroid, nothing resembling unclosed shells or spirals, or otherwise suggesting "perlitic structure on the large scale," * being discernible. There are no empty spaces between these spheroids, but they mutually conform to each other's shape, as if each had been moulded for the place it fills. Generally the adjacent bodies are separated by a secondary layer of impure calcite, whose thickness seems entirely independent of the size of the spheroids it separates. The spheroidal rock is here overlain by a bed of pyroclastic rock, which will again be referred to.

The last occurrence of this spheroidal rock is at B, where it also

* G. H. Williams, The Greenstone Schist Areas of the Menominee and Marquette Regions of Michigan, Bull. U. S. G. Surv., No. 62, p. 167.

forms a small rounded projection jutting into the waves from under a mass of the ordinary diabase, the two rocks being separated by a sharp line of contact, giving the impression that the latter rock, while in a molten condition, moulded itself to the irregularities of the former. The same peculiar forms are even more pronounced here than at F.

Microscopic Petrography.—Somewhat contrary to expectations, the spheroidal basalt did not exhibit any features of exceptional interest under the microscope, the sections showing quite uniformly a finely crystalline amygdaloidal rock, composed of lath-shaped feldspars and a considerable proportion of glass. Porphyritic plagioclases are sometimes present, but are not a constant feature. Secondary alteration is generally well advanced, and the rock is permeated with calcite, chlorite, and sometimes quartz. There can generally be observed a well-defined flow structure, exhibited in the arrangement of the lath-shaped feldspars with their longer axes rudely parallel, in their tangential position around the vesicles, in their frequent curved form, and in the faulting of the larger porphyritic crystals. As a general rule the lath-shaped feldspars appear as single individuals, without polysynthetic twinning; but such extinction angles as were measured, the polysynthetic twinning of the fresher porphyritic feldspars, and the low silica percentage of the rock—less than 50 per cent—indicate that they belong near the basic end of the plagioclase series.

At the lighthouse, the rock exhibiting the structure shown in Plate 7, Fig. 1, is light grayish green, on fresh fracture, with a very compact aphanitic texture. It has been much silicified, and is traversed by a multitude of fine quartz veinlets, together with larger veins of calcite. This veining, combined with the compact porcelain-like texture, renders the rock very brittle, and causes it to fly into small fragments under the hammer. A thin section cut from rock forming the exterior portion of one of the bales, showed it to be composed of small lath-shaped plagioclases in a glassy base, the whole being somewhat obscured by secondary products. Small round amygdules are fairly abundant, generally showing a quartz border with a central filling of chlorite. A section from the interior of one of the bales showed a rock similar to the foregoing, but dif-

fering in the possession of a pronounced flow structure, and in hav-

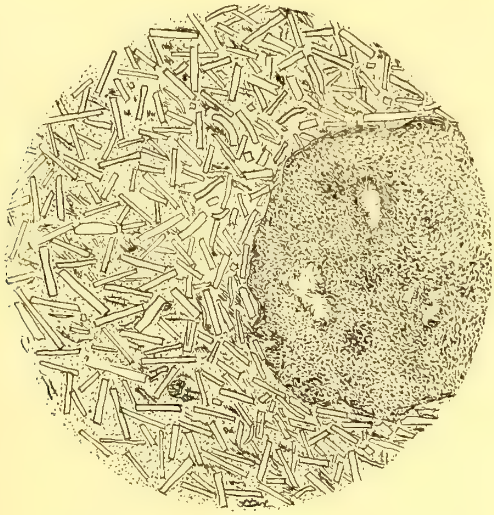


FIGURE 4.—Section of spheroidal basalt from the interior of one of the bales shown in Pl. 7, Fig. 1, with a portion of one of the dense green amygdules. × 21.

ing a general fresher appearance (Fig. 4). The feldspars have arranged themselves tangentially about the amygdules, and where two of the latter lie close together, the feldspars between all lie with their longer dimensions parallel. Several curved crystals were also noted. The amygdules are nearly round, from 1 to 4 mm. in diameter, dark green in color, and almost opaque. They are made up of a felt of very fine needles, with one or more central spots, filled with clear quartz, into which the delicate needles penetrate singly and in little tufted aggregates. With No. 7 Hartnack the needles are seen to be pleochroic, being light green parallel to their length, and colorless at right angles to it. The extinction is approximately parallel. They are suggestive of actinolite, but are too minute for certain identification. A few opaque grains, presumably magnetite, are also present in the slide.

The rock forming the spheroidal masses at the head of the landing stairs (Fig. 1) is dark gray in color, compact in texture, and

shows small amygdules of calcite and chlorite, the latter about 0.75 mm. in diameter. Under the microscope it is seen to consist of a groundmass of lath-shaped and acicular plagioclase and glass, with some sharply bounded phenocrysts of plagioclase, about 2 mm. in length. The plagioclases of the groundmass seldom show rectangular terminations, but fray out in sharp, jagged points. Glass occupies a large proportion of the slide. Small black specks of magnetite are sparingly disseminated through the rock, and there is considerable secondary chlorite.

About thirty feet farther north, a specimen was taken almost identical in macroscopic appearance with the one just described, and certainly from the same general rock-mass. It presents under the microscope, however, a somewhat different appearance, though having the same general texture of groundmass. The most important difference is the presence of augite in small irregular grains and plates. It is not perceptibly pleochroic, extinguishes at a maximum angle of about forty-five degrees from the prismatic cleavages, and is younger than the plagioclases. There is also a relatively greater abundance of small, opaque, black granules, and as some of these are surrounded by gray clouds, they afford the first hint of the presence of titanium. Calcite and chlorite are abundant, filling cracks, amygdules, and interstitial spaces.

The next rock to be described in detail is that forming the large spheroids shown in Plate 7, Fig. 2, at the turn of the path already referred to. It is the most conspicuously porphyritic rock in the area, and weathers to a rough surface, on which the feldspars, varying in length from an eighth to three-quarters of an inch, stand out in relief. Upon fresh fracture the rock is dark greenish gray in color, showing the feldspathic phenocrysts imbedded in a compact groundmass dotted with minute dark-colored amygdules. The large feldspars are seen with the naked eye to be full of dark inclusions, sometimes exhibiting a zonal arrangement. The large spheroid in the illustration was broken completely into fragments, but the rock showed the same structure throughout, with the exception of being less amygdaloidal near the center; it thus differed markedly from the "lava-balls" described by Dana* in the Hawaiian Islands.

*Characteristics of Volcanoes, pp. 9–11.

Under the microscope (Fig. 5) the rock is seen to consist of a finely matted groundmass of lath-shaped and acicular plagioclase, with considerable glass, in which are scattered the porphyritic feldspars already noted. The latter sometimes possess sharp crystallographic boundaries, but are often rounded and corroded, or show jagged step-like outlines, with rims extinguishing differently from the body of the crystal. In general they are two much decomposed to admit of accurately measuring the extinction angles of adjacent lamellæ, but one crystal, less decomposed than the others, gave angles of about fifteen degrees on either side of the twinning plane.

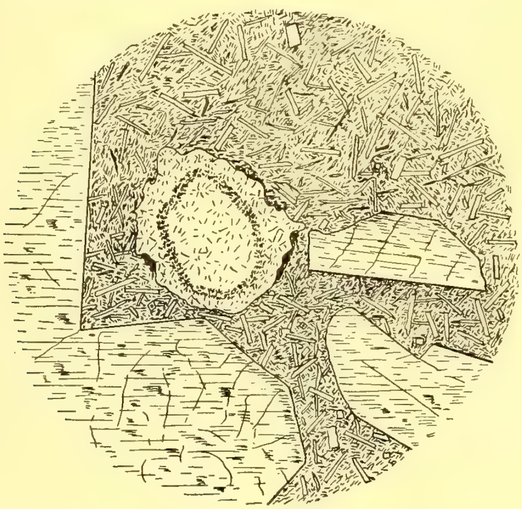


FIGURE 5.—Section of spheroidal basalt composing large spheroid shown in Pl. 7, Fig. 2. The amygdule is filled with chlorite. × 21.

They are full of alteration products, chlorite frequently being observed to replace a portion of one lamella, while the lamellæ on each side are not replaced, thus giving rise to rectangular green inclusions. Instances were observed where a porphyritic crystal had been broken in the magma and the fragments displaced, and one case in which two crystals had apparently been squeezed together. Small round amygdules are moderately abundant, and are generally filled with beautiful aggregates of chlorite; some, however, have an outer

border of quartz, while others have a final interior filling of calcite. The groundmass shows nothing worthy of note beyond an indistinct flow structure. A chemical analysis of the rock is given in column I of the table. It is seen to be a decidedly basic rock, and would probably fall into the class of olivine-free basalts, the magma having solidified before the separation of the pyroxene. The considerable proportion of titanic acid shown in the analysis is interesting, as no titanium mineral is recognizable in the slides.

Down on the beach to the west, this porphyritic rock can be traced through several gradations into the non-porphyritic, aphanitic variety forming the lenses at its southern end. It is accordingly to be regarded as a local variation of the usual compact phase.

The spheroidal rock at F (Fig. 3) is a light gray compact rock, showing no trace of crystalline structure to the eye, and veined with pinkish white calcite. It does not appear amygdaloidal, but some of the smooth water-worn surfaces show a minute laminated structure resembling that observed in many rhyolites. The microscope shows that it was quite a glassy rock, with small lath-shaped feldspars, but is now much obscured by calcite and chlorite. Between the spheroidal basalt and the pyroclastic layer above, is a small lenticular mass of mottled, light gray, rather spongy-looking rock, which apparently belongs to and is continuous with the former. In thin sections it is seen to be a mass of vesicles, separated by walls of microlitic glass and filled with chlorite and calcite. At the time of its eruption this rock must have been of a very light pumiceous haracter.

At B, the last point, going north where the spheroidal basalt can be sharply distinguished from the diabase, the rock is gray and compact and very similar to that at F. Under the microscope (Fig. 6) it is seen to be made up of lath-shaped feldspars with jagged, irregularly terminated ends, and a glassy base. Many of the smaller plagioclases are aggregated into brush-like or feather-like forms, suggesting somewhat the grouping of orthoclase crystals figured by Iddings,* and the augite and feldspar groupings described by Dana † in the Hawaiian lavas.

* Spherulitic Crystallization, Bull. Philos. Soc. Wash., Vol. XI, p. 45, Pl. 8.

† Characteristics of Volcanoes, pp. 320–324.

Figure 6.—Radial grouping of plagioclases in spheroidal basalt at B. × 35.

Secondary alteration is here also well advanced, and the plagioclases do not lend themselves to accurate measurements of extinction angles. The few readings obtainable gave extinction angles of about 17°, indicating labradorite.

THE DIABASE.

Occurrence.—As may be seen by turning to the map, this rock occurs in the southern portion of the area, as a narrow, dyke-like band, traversing the spheroidal basalt, the relative positions of the two near the lighthouse being shown in the accompanying section, B′ B″. As the cliff is here one hundred feet high, and practically vertical, it was not possible to make a close inspection of the eastern contact, but, looking down from above, it appears to be very irregular, and the pyroclastic rock seems to have been ruptured and displaced. There can be little room for error in regarding it as a true igneous contact, for faulting could hardly have taken place along so irregular a surface without the production of considerable friction-breccia, of which there is here no trace. On the north side of the toe-like projection, upon which the lighthouse stands, the pyroclastic rock does not appear, and the diabase can be traced by the eye, as a rather indistinct band along the face of the cliff.

The next opportunity for a close inspection is afforded where the path makes the sharp turn to the east, about one hundred yards south of the old tower, the rock here forming the backbone of the ridge. Its contact with the spheroidal basalt can be followed down on the west side almost to the beach, and seems to indicate its intrusive character, although the very close macroscopic and microscopic resemblances of the two rocks in some cases, make the writer cautious about too positive an assertion. It may, however, be safely affirmed that there is here either a case of very complete intrusion of the diabase into the spheroidal basalt, or else a remarkably rapid transition of one rock into the other; the contact is certainly not one of faulting.

At the turn of the path above referred to, this linear exposure of the diabase apparently terminates, and vain endeavors were made in the field to trace it further. A microscopic slide, from a specimen collected about half way between this point and the mass of the diabase lying west of point G, showed, however, the characteristic features of this rock, and indicates the probable continuity of the two portions. The nature of the ground is such that the connection might easily escape detection in the field.

The line separating the sandstone of point G from the eruptive rock on the west, is defined by a little gully running down to the beach, but the contact between the two is not exposed to view. The contact of the diabase with the spheroidal basalt, as shown in the cutting beside the path, appears to indicate that the former is intrusive, but the evidence on this point is again not as conclusive as might be desired, it being similar to that already adduced at the turn of the path. At one place a roughly rectangular mass of the basalt, about one foot wide and three feet long, was observed, surrounded on at least three sides by the diabase; but this, in the absence of other evidence, might with equal propriety be regarded as a small apophysis of the basalt, or as an included fragment. At any rate, it indicates an *igneous contact* and not a mere sudden gradation of one rock into the other.

Farther north the diabase occurs between A and F, but it was impossible to determine its precise extent, owing to the steepness and insecurity of the crumbling slopes. At F it occurs as shown

in Fig. 3, where it is intrusive into the spheroidal basalt, and, for a few inches only, into the overlying pyroclastic rock. There is also little doubt but what it composes the mass of the cliff above the fragmental layer, but the forbidding character of the rock wall did not invite closer inspection.

At A the land is low, and the eruptive rock disappears, but near point B the diabase again comes into view, and continues exposed, as a narrow strip, up to the sand-bar of Rodeo Lagoon, presenting at several points clear evidence of its intrusive character as regards the sandstone and jaspers, and also passing into modifications which resemble closely the typical forms of the spheroidal basalt. In the corner just north of C, sandstone and shale are exposed near the top of the cliff in a manner to indicate the intrusion of the eruptive rock, but in the little notch between D and E the relations are much more clearly shown. Sandstone and jaspers are here seen to be resting upon, and partly imbedded in, the eruptive rock. The jaspers have been much disturbed, and their layers crumpled and contorted, presenting, close to the contact, a rounded, semi-fused appearance. The sandstone is much darkened in color, considerably sheared, and the shaley bands curved and twisted. At this particular point jaspers may be seen overlying the sandstone, but this does not seem to be their true stratigraphical position; the abrupt manner in which the two beds terminate suggests rather, that they are disrupted portions of strata which have been thrust one over the other during the period of eruptive activity. An inconsiderable amount of typical serpentine was noted, apparently between the eruptive rock and a part of the sandstone. Similar occurrences of this rock were also observed in two other instances where the sandstone is in contact with the volcanic rock, but the patches were too small and obscure to suggest their origin or relationship.

From E northward, the red jaspers may be seen piled in confusion along the top of the cliff, with a general easterly inclination, and separated from the eruptive rock below by an irregular intrusive contact. The latter rock frequently includes fragments of the former, and has forced itself, in long, ragged tongues, between the thin silicious sheets, breaking and crumpling them, and giving their generally sharp edges a rounded and fused appearance. That there has

also been considerable movement and disturbance posterior to the eruption of the diabase, is evidenced by the crushing and calcification which the latter has undergone, particularly north of E.

A small exposure of eruptive rock occurs at M, on the south shore of the lagoon, but is too much decomposed to identify. It appears to be intrusive, and probably belongs to the diabase.

On the eastern border of the map a single point of eruptive rock was observed projecting from the soil, only a few feet from the sandstone, from which it is probably separated by a fault. Whether it belongs with the spheroidal basalt or with the ordinary diabase is not determinable within the limits of the map, and the question is of no immediate importance. It probably is a portion of the latter, and is so mapped.

Microscopic Petrography.—In typical hand specimens the diabase is a dark gray-green rock, with distinct crystalline structure, in which feldspars and a dark mineral, presumably pyroxene, can be distinguished with the naked eye. Under the microscope it generally shows a holocrystalline, coarsely ophitic structure, made up of more or less idiomorphic plagioclase, with the pyroxene filling the interstices in large irregular plates, often optically continuous over a large portion of the slide. Iddingsite * is frequently present, as an important constituent, in large, rounded, idiomorphic forms. Opaque iron ores and apatite are usually present, but vary much in abundance in different specimens. Following German and American usage the rock would probably be classed as a diabase.

The feldspars are, as a rule, too much kaolinized in the more coarsely crystalline specimens to allow of measuring the extinction angles, as only the traces of polysynthetic lamellæ remain; but in some of the finer-grained phases the plagioclases are fresher, and give extinction angles, averaging, in different slides, from 23° to 32° on either side of the twinning plane, which would place it in the labradorite series. It appears very probable that not all the plagioclases are of the same species.

Augite, the only pyroxene present, occurs in large plates and in irregular grains, there being rarely any traces of undoubted

* See "Geology of Carmelo Bay," by Andrew C. Lawson, this Bulletin, Vol. I, pp. 31–36.

crystal boundaries. Occasionally, however, there may be observed roughly square sections with suggestions of truncated corners, and elongated sections presumably from the prism zone. The latter exhibit the cleavage in a system of distinct parallel cracks, usually not very numerous, and seldom running the whole length of the crystal. There is also an irregular parting, shown by coarser cracks, transverse to the prism. Sections perpendicular to the *c* axis generally show a very irregular arrangement of cracks, but the characteristic cleavage of augite can sometimes be made out. The extinction in sections parallel to $\infty P \grave{\infty}$ is about 45°, and in sections transverse to the prism, bisects the cleavage angles. The index of refraction is high, and the double refraction strong, and positive in character.

The augite is generally remarkably fresh, and in many slides shows not the slightest trace of decomposition, in which cases it contrasts strongly with the clouded plagioclases. The colors by transmitted light vary, in different specimens, from a nearly colorless pinkish or greenish white to a deep violet red. Pleochroism is barely discernible or absent in the paler varieties, but becomes very marked in proportion to the increasing depth of color, $\mathfrak{a}$ being light yellowish green, $\mathfrak{b}$ light reddish brown, and $\mathfrak{c}$ a rich violet red. The absorption formula is $\mathfrak{c} > \mathfrak{b} > \mathfrak{a}$. The deep color and pleochroism being suggestive of the presence of titanium,* a portion of the rock containing the most deeply colored crystals was powdered, and the augite separated by means of Klein's solution. The purified powder showed, under the microscope, grains of a deep, clear, amethyst color, which were found to give distinct qualitative reactions for titanium. The specific gravity of the isolated powder was determined as 3.439. The foregoing result thus adds new support to the hypothesis first put forth by Knop,† that the violet

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*A. Knop, Ueber die Augite des Kaiserstuhlgebirges, Zeits. f. Krys. u. Min. Groth., 1885, p. 75.

Rosenbusch, Mikroskopische Physiographie, Stuttgart, 1885, p. 437.

Teall, British Petrography, London, 1888, p. 159.

M. Hunter und H. Rosenbusch, über Monchiquit, ein Camptonitisches Ganggestein, etc. Tscherm. Min. u. Pet. Mitth. N. F. b XI, p. 461.

† *Loc. cit.*, p. 75.

red color of certain augites is always due to the presence of titanium, which he regards as replacing iron in the sesquioxide.

Augite of two different colors is sometimes intergrown, as in Fig. 8, where augite of a pale pink tinge is surrounded by a greenish white variety, the two being optically continuous, and separated by a fine, sharp, irregular line. The intergrowths with hornblende will be described under the latter mineral.

Iddingsite (see Figure 10, page 97) is present in many of the slides of the diabase, in rounded, idiomorphic crystals of various sizes, up to about 1 mm. in length, whose outlines are strongly suggestive of olivine. The color by transmitted light varies from light greenish yellow to a dark, dingy green. The mineral was one of the earliest separations from the magma, and is often entirely surrounded by augite, or hornblende, and sometimes partly so by brown mica. It includes abundant grains of opaque iron ores, and frequently dark brown microscopic crystals of chromite or picotite. In the majority of cases the original crystallographic outline has been lost, presumably by magmatic corrosion, but such sections as show definite bounding planes fall generally into two classes, the one showing hexagonal outlines with nearly equally developed sides, accompanied by a very distinct monotomous cleavage, the other also showing six-sided outlines, but elongated in one direction, so as to form short, stout, prismatic forms, with terminal angles varying from 77° to 90°, usually nearer the latter.

The cleavage is shown by a system of parallel open cracks or gashes, about equally spaced, which subtend two opposite, and generally the two largest, angles of the hexagonal sections, and are perpendicular to two opposite sides. Measurements of the crystallographic angles subtended by the cleavage cracks gave readings ranging from 113° to 142°. These sections are pleochroic, being dark yellowish green parallel to the cleavage, and light greenish yellow at right angles to this position. Under crossed nicols the undecomposed portions show brilliant mottled polarization colors, crimson and green predominating, and the double refraction is therefore strong. The mean index of refraction is rather low.

The distinctly terminated prismatic sections are but slightly pleochroic, and show no cleavage. The interference colors are,

moreover, low. In general, they give a distinct biaxial figure, with a very small axial angle, the arms of the cross merely opening out for a short distance and closing again. The plane of the optic axis lies parallel to the longer axis of the prism, and is, therefore, perpendicular to the cleavage planes. By means of a quarter-undulation mica-plate the mineral was ascertained to be optically negative. The extinction in all cases is parallel to the cleavage traces and the sides of the prism, and the mineral is, therefore, orthorhombic.

These characters serve to establish its identity with iddingsite, as described and named by Professor Lawson, and it can be referred to the same system of axes, $\mathfrak{a} = a$, $\mathfrak{b} = b$, and $\mathfrak{c} = c$; the cleavage is thus parallel to the macropinacoid, the optic axes lying in the brachypinacoid.

In sections parallel to the cleavage planes, there is discernible, with high powers, a distinct fibrous structure, parallel to the edges of the prism, while in iddingsite of Carmelo Bay the fibration is described as being at right angles to the prismatic axis.* This led to a revision of Professor Lawson's sections of carmeloïte, and it was found that in addition to the transverse fibration, which is most conspicuous in the crystals stained brown by limonite, there is discernible in the greener varieties, with high powers (No. 8 Hartnack), another system of fibers which run parallel to the prism edges, and which correspond in every way to those observed in the Point Bonita rock. The transverse fibrous structure seems to be developed or accentuated *pari passu* with the increase of brown coloring matter, and in the deep brown crystals the finer longitudinal fibers become quite masked. In the Point Bonita occurrence, however, the limonitic pigment is entirely absent, and there is no trace of transverse fibration.

The mineral is very fragile, owing, doubtless, to its open cleavage cracks and decomposed state, and could not be separated in a sufficiently pure state for chemical investigation. In sections from the prism zone there is generally noticed an irregular transverse parting, with an accompanying alteration to a green serpentinous aggregate along the crack.

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* *Loc. cit.*, p. 34.

Some slides containing the freshest and clearest crystals were uncovered, and treated for a few minutes with hot, dilute, sulphuric acid, and then with a solution of fuchsine, when the mineral was found to be deeply stained, indicating a gelatinization of the silica, whereas iddingsite is described as yielding pulverulent silica when dissolved as a powder in hydrochloric or sulphuric acid.* For the purpose of comparing the original iddingsite with that of Point Bonita under similar conditions, a typical slide of carmeloïte was subjected to the same treatment, with the result that the iddingsite readily took and held the stain. Thus the last apparent difference between the two minerals vanishes, and they may be considered as identical.

It is impossible to do much more than speculate upon the origin of this mineral, although the probabilities, based on consideration of form, seem to favor its being a pseudomorph after olivine; and it is to be observed in this connection that one of the objections raised by Professor Lawson against this view † may be met; for the bulk analysis of the Point Bonita rock shows a notably high percentage of magnesia.

Hornblende of two varieties, green and brown, occurs in a certain phase of the diabase, the green nearly always being intergrown with the brown, and both showing frequent intergrowths with augite. Sections showing crystallographic outlines are rare, for it separated at the same time as the augite, and is allotriomorphic with respect to the plagioclase. The pleochroism is strong in both varieties; in the brown, $\mathfrak{a}$ is light yellowish brown, and $\mathfrak{b}$ and $\mathfrak{c}$, dark brown; in the green, $\mathfrak{a}$ is light yellowish green, $\mathfrak{b}$, yellowish green, and $\mathfrak{c}$, dark green. The absorption formula is $\mathfrak{c} > \mathfrak{b} > \mathfrak{a}$. The maximum extinction angle observed was about 10°, both varieties extinguishing together when intergrown. The intergrowths of the two with augite are very abundant (Fig. 7), resembling closely those figured by Iddings,‡ in the rocks from Yellowstone Park. The lines separating the two hornblendes from each other, and from the augite, are irreg-

* *Loc. cit.*, p. 31.

† *Loc. cit.*, p. 35.

‡ The Eruptive Rocks of Electric Peak and Sepulchre Mountain, Yellowstone National Park, Twelfth Annual Report U. S. Geol. Surv., Pls. L and LI.

ular, but not in the least jagged or intricate, and the boundary between the different minerals is perfectly sharp and clear, or at most shows only such appearances of transition as would be produced by the overlapping of the two in the thickness of the section. Each mineral retains its optical properties up to the line of separation, and the contrast is fully as marked under crossed nicols. The hornblende is all compact, there being no uralite present.

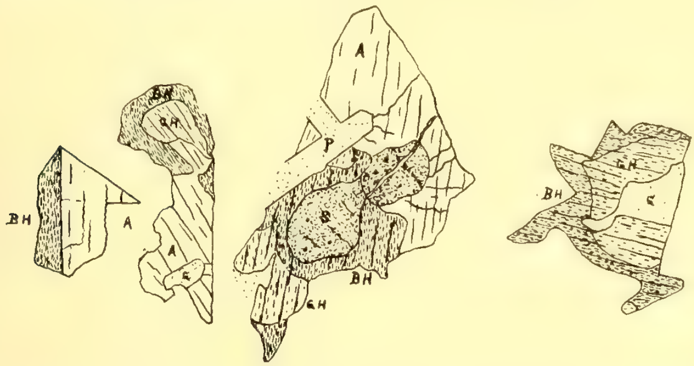

FIGURE 7.—Intergrowths of augite with brown and green hornblende, with included crystals of iddingsite. A, augite ; BH, brown hornblende ; GH, green hornblende ; S, iddingsite ; P, plagioclase ; G, glassy base. × 35.

Brown mica occurs in the same slides as the hornblende, and generally shows no crystal outlines, although two or three hexagonal basal sections were observed. The latter remain dark brown and nearly opaque, with but slight change of color during a revolution of the stage. Sections from the prismatic zone show the characteristic cleavage and strong absorption of biotite.

Opaque iron ore occurs in the finely crystalline phases, as specks and grains of irregular form, or as small, short rods, which often lie across each other like a pile of railroad ties, or the arms on a telegraph pole, and in the more coarsely crystalline specimens as irregular aggregates of some size, and in extremely jagged plates, like those shown in Fig. 8, exhibiting a system of angles of 60° or 120°. It is also abundant in the crystals of iddingsite, generally in the form of little rectangular quadrilaterals. It is either quite fresh, and unaccompanied by alteration products, or else is surrounded by gray clouds of leucoxene. Several examples of a shelly structure

were noted, consisting of black bars, or the edges of plates, meeting at angles of 60° or 120°, and separated by streaks of leucoxene. It is all strongly magnetic, the rocks containing the forms shown in Fig. 8 being capable of being lifted by a weak magnet in fragments from 6 to 7 mm. in diameter. A portion of the rock was powdered, and the opaque grains extracted with a weak horseshoe magnet. These, after being boiled for some time in hydrochloric acid, gave distinct reactions for titanium. A portion of the slide shown in Fig. 8 was uncovered, and treated for about one and one-half hours with hot strong hydrochloric acid without dissolving the opaque masses. The only effect of the acid was to reveal a distinct fibrous, or fine platy structure not noticeable in transmitted light, but conspicuous in incident light, and consisting of narrow black strips meeting at angles of 60° and 120°, and separated by narrow bands of a blue-gray substance. Teall, in his paper on the Whin Sill,* has suggested that magnetite and ilmenite are probably frequently intergrown, and the observations of the writer seem to corroborate this view. Both magnetite and ilmenite are probably present, but there are various intermediate mixtures which cannot be referred definitely to one or the other mineral. The large ragged form shown in Fig. 8 resembles very closely some intergrowths of magnetite and ilmenite described and figured by Teall in his paper.

Apatite can generally be detected in the fresher and more coarsely crystalline slides, and is sometimes quite abundant. It occurs, included in the feldspars and augite, as rather slender colorless prisms, showing the usual blue-gray interference colors, and isotropic hexagonal cross sections of apatite.

Having described in detail the separate minerals we turn now to a consideration of the special features of particular occurrences of the diabase. On the neck between the lighthouse and the fog siren it is a dark green rather coarsely crystalline rock, with a somewhat peculiar structure. Both on weathered surfaces and fresh fracture it appears as a very coarse felt of long, blade-like crystals, the augite, plagioclase, and iron ores being recognizable with the unaided eye. One feldspar was noted about 2 cm. in

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* Chemical and Microscopical Characters of the Whin Sill, Quart. Jour. Geolog. Soc., Vol. XL, pp. 650–652, Pl. XXIX.

length and only about 1 mm. in width, while the other minerals show similar elongated forms. Under the microscope (Fig. 8) the

FIGURE 8.—Section of diabase near lighthouse, with large mass of ilmenite (and magnetite). *a*, light greenish augite; *á*, light pinkish augite; *p*, plagioclase; *c*, chlorite. × 35.

rock shows a coarsely crystalline ophitic structure, in which occur irregular patches of a dense green groundmass in which little can be made out except remnants of lath-shaped feldspars, grains of opaque iron ores, phenocrysts of plagioclase, and much secondary quartz, chlorite, and light green hornblende. The ophitic portion of the rock consists of much decomposed idiomorphic plagioclases, augite in large irregular plates, and opaque iron ores ranging in size from small grains up to aggregate 7 mm. in length, and large masses with the form and appearance of ilmenite (Fig. 8). The augite is colorless to light greenish or pinkish shades, and with little or no pleochroism. It shows more signs of alteration than usual, and is sometimes bordered by little plates and tufts of light green secondary hornblende, which penetrate it irregularly and grow as if rooted in its surface. Apatite is abundant, in long slender prisms, which pass uninterruptedly through plagioclase, augite, and the dense groundmass, indicating that the rock solidified quietly *in situ*. That this rock is of the nature of a local mod-

ification or basic segregation of the more normal diabase, is evident from the fact that it can be traced both east and west from the middle line (see section B′ B″), into rock indistinguishable from the latter; moreover, a single hand specimen was obtained near F, showing both aspects of the rock present in the same piece.

At the turn of the path just south of the spheroids shown in Plate 7, Fig. 2, the diabase has a somewhat lighter green color and appears more granular in texture. In thin section it shows a nearly holocrystalline ophitic structure, made up of plagioclase, augite, opaque iron ores, and green serpentinous patches which are evidently remnants of iddingsite. There are no amygdules, but secondary alteration is well advanced, and chlorite and serpentine are scattered through the slide. The iron oxides are only moderately abundant and are accompanied by gray clouds of leucoxene. Apatite was not detected in the slide examined, but may be present in the rock, as it shows a tendency to occur in groups or colonies of crystals, so that different slides from the same rock often show it in varying abundance. The augite is light pinkish red, with little or no pleochroism. It is the freshest mineral in the slide, showing only slight traces of decomposition in the presence of a yellow stain bordering some of the cracks.

At the point where the path crosses the contact with the sandstone, the diabase is exposed as a crumbling mass in the cutting by the path side. The undecomposed nodules show that it is a dark green distinctly crystalline rock of granular, almost gabbroitic, appearance. Under the microscope it shows a beautifully sharp ophitic structure (Fig. 9), with not a trace of glass, and is made up of plagioclase, augite, iddingsite, brown and green hornblende, and brown mica. There are present also a few crystals of apatite, and occasional grains of magnetite. The plagioclases are generally cloudy, but the augite is clear and fresh, being colorless to very light green or pink. The iddingsite occurs in rounded decomposed crystals of considerable size and is very abundant (Fig. 10), giving to the rock its green color. One crystal was observed surrounded by magnetite as an original inclusion. It is in this phase of the diabase that the intergrowths of hornblende and augite occur, as described in a former paragraph. A chemical analysis of this rock is given in column III of the table of analyses.

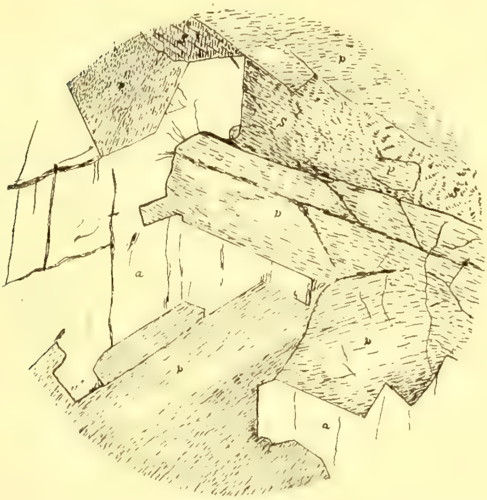

FIGURE 9.—Section of diabase, showing holocrystalline ophitic structure. *a*, augite; *p*, plagioclase; *s*, serpentinous patches, probably remnants of iddingsite. × 35.

FIGURE 10.—Section of diabase, showing rounded crystals of iddingsite, and intergrowths of augite and hornblende. *a*, augite; BH, brown hornblende; GH, green hornblende; P, plagioclase; *s*, iddingsite. × 21.

From point A northward as far as D, the diabase presents puzzling variations, which it is difficult to account for, save on the supposition that the rock at the time of its eruption did not move as a mobile molten liquid, but as a somewhat viscous mass, composed of a magma heavily charged in places with solid, or partially solid, fragments, of a compact spheroidal rock resembling the basalt below. Upon cooling, the magma crystallized in its deeper-seated portions as the normal diabase, filling all the interstices between the fragments, and forming what are now the more massive portions of the cliff. Whether the included fragments were formed from the magma itself by a partial cooling followed by renewed movement, or whether they were derived from the spheroidal basalt below, it does not seem possible to determine. From certain internal evidence afforded by one of the spheroids the former hypothesis seems, however, most probable, and Miss Raisin * has advanced a like suggestion to account for a similar association. Certain it is, that in passing along the foot of the cliff, spheroids composed of aphanitic rock are encountered at various places, so intimately associated with the coarsely crystalline diabase that it is impossible to separate them into two distinct portions.

Aside from these apparent inclusions, the diabase presents its usual macroscopic appearance of a dark green distinctly crystalline rock. Slides from between C and D exhibit the distinctive character of the diabase, including the presence of iddingsite. The augite is more deeply colored here than elsewhere, and more strongly pleochroic. At point E the diabase becomes more finely crystalline and shows abundant white amygdules. Under the microscope, it is seen to be composed of lath-shaped plagioclases, with the augite in scattered irregular grains, and is evidently a transition rock, indicating an approach to surface conditions of cooling. It is much decomposed and full of calcite in the form of amygdules, veins, and replacements. This conspicuous calcification is a marked macroscopic feature of the diabase from E northward, showing itself in veins and stringers throughout the shattered mass.

A specimen from the central portion of one of the spheroids

* The Variolite of the Lleyn and Associated Volcanic Rocks, Q. J. G. S., Vol. XLIV, p. 152.

associated with the diabase, about half way between B and C, shows a compact gray rock of cryptocrystalline texture, which, under the microscope, is seen to be composed of a groundmass of lath-shaped plagioclases and unindividualized glass, in which are scattered a few large feldspathic phenocrysts. Both the lath-shaped and porphyritic crystals are unusually fresh, and give extinction angles ranging from 23° to 28°, the most common angle being about 25°. This would indicate their position to be in the labradorite series. Opaque iron ores are present in the form of minute specks, and there are a few small round amygdules of calcite and chlorite. A chemical analysis of this rock is given in column IV of the table.

A fragment from the exterior of a similar spheroid at C is identical in macroscopic appearance, but shows a more glassy structure under the microscope. In addition to the ordinary lath-shaped plagioclases, which are often of unusual length, there also occur smaller individuals which are aggregated into open radial and brush-like groups, which may be regarded as imperfect spherulitic growths.* They are more perfect examples of a similar structure already described in connection with the spheroidal basalt. Similar radial groupings of the feldspars have been noted by Miss Raisin † in the spheroidal basalt of the Lleyn, and by Cole and Gregory ‡ at Mont Genèvre.

Variolitic Facies.—The very constant association which appears to exist in European localities between spheroidal diabase or basalt and variolitic structure, led to a careful search for varioles in the more compact phases of the rock under investigation. The effort met with success, although the varioles were found only in one spot, and are certainly not a constant concomitant of the spheroidal forms, as they were not detected at all in the lower basalt. About midway between C and D, near the base of the cliff, and therefore at some depth within the eruptive mass, small round bodies were observed standing out from the weathered surface of an imbedded spheroid. They were of the same gray color as the rock, which,

* Iddings, Spherulitic Crystallization, Bull. Phil. Soc. Wash., Vol. XI, p. 459.

† *Loc. cit.*, p. 153.

‡ The Variolitic Rocks of Mont Genèvre, Q. J. G. S., Vol. XLVI, p. 313, Plate 13, Fig. 5.

on fresh fracture, shows a very dense texture, with no visible crystals. When it is cut with a lapidary's disk, the varioles appear as round dark-gray spots, about 4 mm. in diameter, surrounded by a somewhat lighter colored groundmass, and separated from the latter by minutely wavy lines of demarkation, similar to those which bound the varioles in Delesse's colored plate.* Numerous very fine cracks traverse both groundmass and varioles.

Under the microscope (Fig. 11) the varioles are seen to be com-

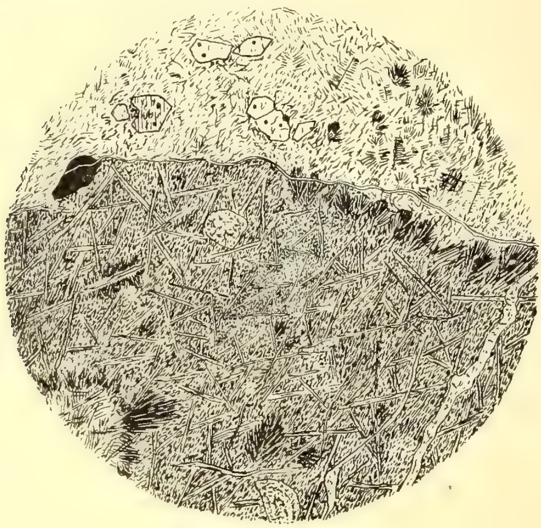

Figure 11.—Section of variolite. The lower portion shows part of a variole, while above is the lighter gray groundmass, the two being separated by a secondary crack. In the variole can be seen the pseudocrystallites, the augite brushes, some irregular cracks, and two vacuoles filled with chloritic aggregates. The groundmass shows such of the more delicate forms as are visible with low power, and some crystals of iddingsite. × 21.

posed of an open meshwork of straight, colorless rods with rather indefinite boundaries, which strongly suggest at first sight the long, lath-shaped plagioclases of some glassy rocks. The spaces between these rods are filled with microlites in radiating brush-like aggre-

* Sur la Variolite de la Durance, Ann. des Mines, sér. 4, t. XVII, Plate 1, Fig. 3.

gates, some comparatively close and massive, with a bronze-brown color, others in more open, delicate, colorless forms. Both classes of aggregates appear to have developed independently of the rods, which intersect the brushes in different directions. Numerous cracks, filled with some colorless mineral, traverse the varioles irregularly, and when they are narrow and straight are not distinguishable from the rods.* Under crossed nicols the different brushes and groups show partial and distorted black crosses, while the rods and cracks polarize irregularly like aggregates. With high powers the rods appear as spaces filled with some transparent material into which project the ends of microlites on either side. This material does not effervesce with acids, and is probably feldspathic, the rods corresponding to the pseudo-crystallites of M. Michel Lévy.†

The microlites composing the dense brown brushes could not be separated distinctly with high powers. With crossed nicols they give suggestions of bright polarization colors, and extinguish at a considerable angle, apparently about 40°. They are probably augite.

The light gray groundmass, in which the varioles are imbedded, is seen under the microscope to be made up of a mass of delicate arborescent growths suggesting the hoarfrost on a window, or a forest of minute conifers prostrated by the wind. A few of the clusters radiate from a central point, others from a short line, but by far the most common arrangement is that of a central rib, to which the microlites stand perpendicular on either side, recalling no image so suggestive as a young symmetrical fir-tree. With high power, the microlites appear as little transparent colorless rods with blunt, rounded ends, showing parallel extinction and blue-gray interference colors. They are doubtless feldspars. They exhibit none of the "cone-in-cone" structure as described by Cole,‡ but,

*J. W. Gregory, The Variolitic Diabase of the Fichtelgebirge, Q. J. G. S., Vol. XLVII, p. 56.

†"Mémoire sur la Variolite de la Durance," Bull. Soc. Géol. France, 3me Sér., Vol. V, p. 238.

See also Delesse, Sur la Variolite de la Durance, *loc. cit.*, p. 118, with cut.

‡On Some Examples of Cone-in-Cone Structure, Min. Mag., Vol. X, No. 46, p. 136, 1893.

when radially placed, either spread apart as they approach the periphery, or else the spaces become filled with what appear to be still smaller microlites arranged at right angles to the principal rays.

The radial grouping about a line instead of a point, results in rather curious interference figures with crossed nicols. When the longer axis of the aggregate is parallel to a principal section of one of the nicols, the figure consists of two parallel black lines at right angles to this axis, accompanied by two dark brushes which are outside of, and perpendicular to, these lines. As the stage is rotated in one direction, the brushes vanish, the bars open into hyperbolas, and, when the stage has rotated 90°, new parallel lines appear in the center of the figure at right angles to their former position. If the rotation be in the other direction, the phenomenon is reversed, the hyperbolas straighten back into bars, and the parts of the figure move from without inward.

The groundmass is wholly free from the pseudocrystallites which are so conspicuous in the varioles, and contains very few of the more massive bronze-brown aggregates. The varioles generally grade abruptly into the groundmass without any sharp microscopic boundary; but they are sometimes separated by cracks * as shown in the figure. The crack, however, does not always adhere to the true surface of the variole.

Small crystals of iddingsite, often showing sharp crystallographic boundaries, occur scattered through groundmass and varioles. They are generally somewhat decomposed, but the hexagonal section shown in Fig. 11 is comparatively fresh and transparent, showing the cleavage in a system of sharp parallel lines instead of open gashes. They gelatinize readily with acids and show the optical properties of iddingsite. The crystals contain numerous microscopic inclusions, some of which are magnetite; but others are dark brown in color, semi-transparent, singly refracting, and apparently of octahedral habit. They are not affected by hot hydrochloric acid, and are probably picotite or chromite. The presence of iddingsite in this spheroid is an argument in favor of its being a variation of the diabase, as this mineral has not been detected in the lower

* E. Geinitz, Ueber einige Variolite aus dem Dorathale bei Turin. Tscherm. Min. u. Petr. Mitth., Bd. I, 1878, p. 136.

spheroidal basalt. Its occurrence in well-developed crystals in a rock otherwise showing only microlitic forms, strongly emphasizes, moreover, the fact that it was an early separation from the magma.

The varioles found, were too few in number to throw any new light upon the relation existing between their occurrence and spheroidal structure. There appears to the writer, however, no good reason for considering them in this case as due to secondary devitrification,* but they seem rather to owe their origin to some physical circumstances † attendant upon the original cooling of the magma, Miss Raisin having come to a similar conclusion in regard to the variolite of the Lleyn.‡ Nothing like the perlitic cracks of a devitrified tachylyte have been detected, and the variolitic structure must apparently be regarded as closely related to the radial groupings of plagioclase previously described, which are certainly not secondary in origin; indeed, Lœwinson-Lessing § has shown that the one structure can be traced directly into the other.

With the exception of the very doubtful occurrence described by G. H. Williams, || the writer is not aware of any description of variolite from an American locality.

THE PYROCLASTIC ROCKS.

These have been found in only two places in the area, near the lighthouse and at F. At the former place it occurs as a rather thin, irregular, and interrupted band, running diagonally down to the water's edge on the south side of the cliff. (See section B′ B″.) It consists of rounded and angular fragments of very vesicular rock, cryptocrystalline in texture, and resembling the rock of the spheroids. These fragments average two to three inches in diameter,

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* G. A. J. Cole, On Some Additional Occurrences of Tachylyte, Q. J. G. S., Vol. XLIV, p. 300.

Also, Cole and Gregory, The Variolitic Rocks of Mont Genèvre, Q. J. G. S., Vol. XLVI, p. 314, 1890.

† F. Lœwinson-Lessing, Die Variolite von Jalguba im Gouvernement Olenez, Tscherm. Min. u. Petr. Mitth, B. 6 N. F., pp. 299–300, 1885.

‡ *Loc. cit.*, p. 297.

§ *Loc. cit.*, p. 156.

|| *Loc. cit.*, p 173.

and are imbedded in a matrix of more finely comminuted volcanic material.

At F the exposure is more extensive and more readily accessible, the fragmental rock occurring as a sheet of very irregular thickness, reposing upon an uneven surface of spheroidal basalt, and having a general inclination to the east or southeast. (See Fig. 3.) It is here composed of fragments of light gray aphanitic amygdaloidal rock, similar to that forming the spheroids below it, and ranging in size from a fraction of an inch to a foot or more in diameter the average size being about three inches. These fragments are imbedded in a rust brown matrix, which is apparently made up of finely comminuted volcanic ejectamenta. In general the pieces are more or less rounded, but sharply angular fragments are also abundant. This bed is overlain by the diabase, a portion of the latter rock being also intrusive below it in what is apparently a small apophysis. Although the fragmental rock was evidently laid down upon an uneven surface, much of its present irregularity, especially of its upper surface, appears to be due to subsequent disturbances, probably coincident with the intrusion of the diabase. The testimony afforded by this bed of agglomerate as to the divisibility of the eruptive rocks of the area into those belonging to at least two periods of volcanic activity, is of the most emphatic and positive nature, and is enough to establish the surface character of the spheroidal basalt.

RELATIONS OF THE ERUPTIVE ROCKS TO EACH OTHER.

It has been shown that the eruptive rocks are of two periods of eruption, inasmuch as one portion was extravasated as a surface flow, while the other is intrusive. Of these two periods that of the surface flow preceded the intrusion of the diabase, for the spheroidal basalt is generally observed underlying the diabase, and has been invaded by it. The only exception to the inferior position of the spheroidal basalt is found in the place held by the comparatively large mass forming the eastern side of the point. The latter rock differs from the normal spheroidal basalt in two other respects than that of relative position;—it contains abundant inclusions of jasper, and at one place shows augite in thin sections. Moreover, being

above the beds of pyroclastic rock (see section B′ B″), it loses its most important title to being considered a surface rock, and may possibly belong to the diabase and be intrusive, notwithstanding its typical spheroidal structure. That such structure is not wholly incompatible with the idea of intrusion has been shown by Gregory.* It seems most probable, however, that this also was a surface flow which succeeded and covered the agglomerate, the diabase subsequently being intruded between the members of the surface series, as shown in section B′ B″, the fragments of jasper being in this case caught up by the flow, and derived from a lower horizon than that of the bed mapped.

Chemically the two rocks are seen to be practically identical, there being as much variation between rocks undoubtedly of the same eruption as between those of different age. The analyses indicate that the microscopic differences observed in the rocks are mainly conditioned by physical causes, and that the absence of a mineral in one rock is not by any means an indication that the elements required for its formation are lacking in the general magma, or that it would not have developed under somewhat different conditions of solidification.† The presence of augite in the diabase and its absence in the spheroidal basalt can be regarded as due only to physical conditions of cooling, and is analogous to the fact recorded by Professor Lawson ‡ in regard to the carmeloïte of Carmelo Bay,—augite there occurring in the plug rock but not in the surface flows.

It is unfortunate that the generally decomposed or altered condition of the spheroidal basalt prevented a more thorough chemical comparison with the diabase, only one analysis of the former being made, and that of a somewhat local phase.

The considerable proportion of titanic oxide is noteworthy, and in view of its supposed influence upon the fusibility of rock magmas, as pointed out by Dr. Becker,§ it is natural to infer that it plays

* *Loc. cit.*, pp. 58, 59.

† J. P. Iddings, The Crystallization of Igneous Rocks, Bull. Philos. Soc., Wash., Vol. XI, p. 92, and The Mineral Composition and Geological Occurrence of Certain Igneous Rocks in the Yellowstone National Park, *ibid.*, p. 213.

‡ *Loc. cit.*, p. 44.

§ See H. W. Turner's paper on the Geology of Mount Diablo, Bull. Geol. Soc. Am., Vol. 2, p. 386.

some part in bringing about the spheroidal and variolitic structures; but the recorded observations of other writers do not lend much support to this view. Thus, while Gregory* describes the diabase of the Fichtelgebirge as showing an abundance of ilmenite and leucoxene, the analyses by Lœwinson-Lessing† of the Jalguba variolite, and by Delesse ‡ of the Durance occurrence, show no titanium. This, however, does not necessarily prove its absence, unless it was particularly sought for.

Analyses of Eruptive Rocks of Point Bonita.

—	I.	II.	III.	IV.
SiO_2	49.45	46.28	45.59	44.71
TiO_2	2.23	3.54	......	2.88
Al_2O_3	17.58	12 96	20.99	15.54
Fe_2O_3	3.41	4.67	2.49	3.06
FeO	3.41	6 06	4.36	6.43
MnO	trace	trace	......	trace
CaO	7.20	10.12	7.57	10.50
MgO	4.05	8.71	8.95	6.80
Na_2O	5.83	3.75	4.89	2.55
K_2O	1.57	calc. as Na_2O	calc. as Na_2O	calc. as Na_2O
H_2O	ig. 4.34	3.34	ig. 5.06	ig 5 90
P_2O_5	not det.	not det.	not det.	not det.
	99 07	99.43	99.90	98.37
Sp. gr.	2.738	2.921	2 707	2.858

I. Spheroidal basalt from exterior portion of large spheroid shown in Pl. 7, Fig. 2.

II. Diabase, from the turn of the path just south of above spheroid.

III. Diabase, near the fault line where crossed by path. Figs. 9 and 10.

IV. Spheroid in the diabase about half way between B and C.

THE SEDIMENTARY FORMATIONS.

Character and Occurrence.— Leaving out of consideration the unconsolidated deposits of Pleistocene age, the major part of the sedimentary area is occupied by the San Francisco sandstone, which

*Loc. cit., p. 54.

†Loc. cit., p. 294.

‡ Bull. Soc. Géol. France, 2d sér. t. vii, p. 430.

is divided into two portions by a formation of bedded jaspers. The southern and larger portion is well exposed along the shore, and afforded good observations for dip and strike. This rock is described at some length by Blake,* Newberry,† and Whitney.‡

It is here a fine-grained sandstone of light gray color, in well-defined beds, varying from a few inches to several feet in thickness. The thinner beds are crowded with dark, carbonaceous spots, which are evidently remnants of vegetable matter, lying with their flat sides parallel with the planes of lamination. Thin lenticular sheets of undoubted coal, up to an inch in thickness, were also observed. Beyond these fragments, however, the rock seems barren of organic remains.

The strike at H is well defined by the series of parallel points, the dip being westerly. Towards K the angle of dip increases, and the beds become thinner and more carbonaceous. At G the sandstone is somewhat disturbed, but shows a well-defined dip to the northeast, which it appears to maintain without much change until K is reached. At this point all bedding is lost, and the rock shows indubitable signs of crushing and disturbance, indicating a rending or faulting of the strata rather than a simple fold. It is to be noted that of the considerable thickness of strata exposed east of K, but a very small portion again appears between K and G (see Section A′ A″). Two or three isolated outcrops of the sandstone occur in the dotted area of the map, and it is seen in conjunction with the ruptive rock near C and D, but is elsewhere concealed by the Pleistocene deposits.

The jaspers possess here the very characteristic features which constantly accompany these remarkable rocks about the shores of San Francisco Bay, and in other portions of the Coast Ranges. Those of this particular locality have been described or referred to by earlier observers, as has been already noted.§ Dr. Becker has brought forward a theory of metamorphism‖ to account for their

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**Loc. cit.*, pp. 145–154.

†*Loc. cit.*, p. 12.

‡*Loc. cit.*, pp. 76–78.

§*Ante*, p. 73.

‖*Loc. cit*

highly siliceous character, which cannot be regarded as quite satisfactory, and the conditions of their deposition and silicification must be considered as a still unsolved problem. Near the eruptive rock they have been much disturbed, but the general dip, near the northwest corner of the map, seems to be in a southerly direction. The only satisfactory observation was that obtained at J, where the bed crops out on the hillside as a ledge about fifty feet long. The dip here is southerly, which would carry the jaspers under the sandstone to the south. Just outside the eastern limits of the map the jaspers again outcrop, and the fact that this second exposure is in the line of strike, has been deemed sufficient warrant for the projection of the mapping across the doubtful dotted area.

Lastly, the sandstone is exposed again at the base of the hill on the south shore of Rodeo Lagoon, but is too decomposed and soil-covered to show dip or strike. It appears to be rather coarser here than in the southern area, and shows evidence of shearing and disturbance. Several angular fragments of jasper, about three inches in diameter, were observed imbedded firmly in the sandstone, a fact that militates against any theory calling for a general simultaneous silicification of the whole jaspery series. Like the jaspers, this rock again occurs just outside of the map, and presumably extends across the intervening space, as mapped.

The foregoing portion of the sedimentary series thus appears to form a syncline, whose axis extends approximately northwest and southeast. Of the southwestern limb of this syncline but a small portion remains, the rest, as will be shown, having been displaced by faulting. The jaspers do not reappear in the southwestern part of the map, but that they underlie the sandstone at no great depth is indicated by the numerous inclusions of jaspery fragments in the eruptive rock from the landing northward, and by the occurrence of large loose blocks, bearing every mark of having been included masses, lying on the beach just east of G.

Relations to the Eruptive Rocks.—The diabase has been shown to be intrusive into the sandstones and jaspers, and is, therefore, of later age. The relative age of the spheroidal basalt is, however, not so easily determined. Its present position is, undoubtedly,

below the sedimentary series, the latter everywhere dipping away from it in a general easterly direction. Moreover, the beds of pyroclastic rock, and all structural planes which were presumably at one time parallel to the original surface of the flow, show a similar easterly inclination, which would carry them under the sedimentary rocks. But here another factor enters into the problem in the occurrence of a fault, extending, as shown on the map, from G to the stream mouth near A, and possibly further north. The curtailment of the western limb of the syncline, and the reappearance, west of K, of only a small part of all the sandstone beds, cannot be explained otherwise than by the assumption of such a fault, and cumulative evidence pointing to its existence might readily be adduced. The faulting, in all probability, accompanied the intrusion of the diabase, but it is not at all unlikely that the differential movement continued after the solidification of the latter, and was the cause of much of its subsequent shattering.

Admitting the fault into the problem, it is at once seen that two alternatives are suggested,—either the spheroidal basalt was poured out anterior to the deposition of the sedimentary strata, and was afterwards elevated to its present position, or else it is a flow of much more recent date extravasated upon the top of the sedimentary series, and owes its present inferior position to the fact that it is upon the down-throw side. The former view is most in harmony with the present position of the spheroidal basalt, its easterly inclination, the general tilting to the east of the beds along the top of the cliffs north of A, and the upturning of the faulted edges of the sandstone beds at G, accompanied by the crushing at K, while the latter is chiefly supported by the fact that the spheroidal basalt and the diabase are so nearly identical in chemical composition, and appear to have suffered equally from the effects of time. On the whole, the former view seems to have most in its favor, and to be most in agreement with what is known of other occurrences of similar spheroidal basalt in the vicinity, the latter being, as far as noted, always closely associated with jaspers and the San Francisco sandstone, indicating a contemporaneous rather than a subsequent origin for the basalt.

Spheroidal basalt, apparently similar to that described, has been

noted by the writer at Tiburon, Marin County; at Port Harford, San Luis Obispo County; and on the summit of the north peak of Mount Diablo. It is noteworthy that in these widely separated occurrences the rock is always associated with the red jaspers, and with what is apparently the San Francisco sandstone. The Mount Diablo rock is referred to by Turner* as apparently "a greatly decomposed diabase," he making no mention of its spheroidal structure, or of a beautiful feather grouping of plagioclases, which it exhibits under the microscope.

THE ORIGIN OF THE SPHEROIDAL STRUCTURE.

Spheroidal structures, similar to those described in this paper, have been noted by several writers in connection with aphanitic diabase or basalt, and various theories have been advanced to account for them. Without attempting an exhaustive historical review, the following references may be said to have a close bearing on the forms under discussion:—

In 1875 Mallet† explained the occurrence of the spheroids in many basalts as due to the weathering and exfoliation of "pointed pieces" of basaltic prisms. Bonney,‡ in the following year, developed this idea, by showing that the tendency of a mass cooling from several different centers would be to produce spheroids by contraction. While the foregoing theories undoubtedly offer true explanations of many occurrences, they are inadequate for the case in hand. Both, starting from roughly cubical forms, require that the resulting spheroids should be separated by an amount of material vastly greater than that actually found between the Point Bonita spheroids. In 1881 Bonney§ referred briefly to a spheroidal structure in an altered basalt of Porth-din-Lleyn, but offered no

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*The Geology of Mount Diablo, California, Bull. Geol. Soc. of Am., Vol. 2, p. 385.

†Origin and Mechanism of Production of the Prismatic Structure of Basalt, Phil. Mag., 4th Ser., Vol. 50, p. 220.

‡On Columnar, Fissile, and Spheroidal Structure, Q. J. G. S., Vol. XXXII, p. 151, 1876.

§On the So-called Serpentine of Porth-din-Lleyn, Q. J. G. S., Vol. XXXVII, p. 50.

explanation therefor. Professor Lawson,* in 1885, described the so-called "concretionary structure" in the much altered basic eruptives of the Lake of the Woods region, but without discussing its origin. G. H. Williams † in 1890 described and figured a spheroidal structure in the aphanitic greenstone near Marquette, and pointed out the identity of the forms with those described by Professor Lawson. He shows that "they are in no sense concretionary," and favors the hypothesis of Rothpletz,‡ that they are due to brecciation and rubbing caused by intense orographic pressure. Cole and Gregory,§ in the same year, saw in "the irregular shapes and involuted surfaces of the diabase of Mt. Genèvre the evidence of lavas rolling over among themselves." Gregory,|| in 1891, describing the spheroidal diabase of the Fichtelgebirge, suggests that the diabase cooled rapidly and contracted into spheroids, which were then rolled over among themselves. In the present year Miss Raisin,¶ describing the spheroidal structure in the rocks of the Lleyn, regards it as being produced by a spheroidal parting during cooling, the spheroids being subsequently moved and modified by a second influx of lava.

It seems to the writer that none of the foregoing theories offer a complete explanation of the structures described in this paper, although the idea advanced by Messrs. Cole and Gregory appears to afford the most suggestion. The close contiguity of the spheroids or bales, the absence of any considerable amount of interstitial material, and the striking evidence which they show of former plasticity, are facts not to be reconciled with any theory calling for a

* Report on the Geology of the Lake of the Woods Region, by Andrew C. Lawson, M. A., Geological and Nat. Hist. Surv. of Canada, 1885, pp. 51–53.

† The Greenstone Schist Areas of the Menominee and Marquette Regions of Michigan, by G. H. Williams, Bull. No. 62, U. S. Geol. Surv., Wash., 1890, pp. 166–168.

‡ Ueber Mechanische Gesteinsumwandlungen bei Hainichen in Sachsen, part 2, Zeitschr. Deutsch. Geol. Gesell., Vol. 31, pp. 374–397. Cited by Williams, but not accessible to writer.

§ On the Variolitic Rocks of Mont Genèvre, Q. J. G. S., Vol. XLVI, p. 316.

|| On the Variolitic Diabase of the Fichtelgebirge, *ibid.*, Vol. XLVII, p. 60.

¶ Variolite of the Lleyn and Associated Volcanic Rocks, *ibid.*, Vol. XLIX, p. 152.

spheroidal parting subsequent to solidification, or for a rounding by brecciation.

It is when we turn to the forms of structure exhibited by the modern basic lavas of the Hawaiian Islands, that abundant points of analogy appear, and it becomes evident that we are dealing with a structure taken on by the lava at the time of its original fluidity and movement,—it is essentially a *flow* phenomenon. As is well known, the Hawaiian lava is erupted in two forms,—as *aa* and as pahoehoe. The latter is described as being, at the time of its eruption, as "liquid as water," * and, as may be seen in the illustrations of Dana † and Dutton, ‡ solidifies in smooth ropy forms, very suggestive of the bale-like masses shown in Pl. 7, Fig. 1. Now, if by any means the viscosity of this pahoehoe could be slightly increased, its movement would become more sluggish, and the rope-like forms would thicken up, shorten, and approach more nearly the form shown in Fig. 2; or, in other words, we might have a form of lava intermediate between the pahoehoe and the *aa*. It is in this connection that the high percentage of titanium shown in the analyses becomes of importance, and it seems quite possible that to its presence may be due the supposed slightly greater viscosity required by the theory.

In brief, then, it is supposed that the spheroidal basalt of Point Bonita flowed as a viscous pahoehoe, one sluggish outwelling of lava being piled upon another to form the whole mass of the flow. In portions of the area this structure remains substantially unmodified, as shown in Pl. 7, Fig. 1; but elsewhere these bales, while still plastic, were subjected to forces incident upon the forward movement of the whole mass, and were rolled into more spherical forms, or flattened into lenses. It is to be noted that this hypothesis harmonizes with two facts observed in connection with the bales near the lighthouse (Pl. 7, Fig. 1), viz., that the searching action of waves and weather reveals in them a more or less distinct differentiation into an exterior shell and an inner core, and that the microscopic flow structure is more conspicuous in the core than in the shell; for, as the crust of each bale cooled, the central portion would still tend

* See Dana, Characteristics of Volcanoes, p. 192.

† *Loc. cit.*, Pls. VII and XI.

‡ Hawaiian Volcanoes, Fourth Ann. Report U. S. Geol. Surv., Pl. XVIII.

to flow onward, and consequently to separate itself from the cooling shell, it being an example in miniature of the lava tunnels of Hawaii. Where this separation was taking place, the lava would be under diminished pressure, and the included vapors would expand into vesicles, as was found to be the observed fact.*

As regards the probable position of the former center of volcanic activity,—the coarseness of the ejected fragments composing the pyroclastic rock, the general lack of regularity and continuity of the beds, the spheroidal and bale-like forms of the basalt, and the occurrence of both surface and intrusive rocks,—all indicate that the volcanic focus was not far away, and probably lay to seaward at some little distance off the present coast.

The writer's grateful acknowledgments are due to Prof. A. C. Lawson, under whose supervision the foregoing investigations were conducted, for his unfailing kindness in regard to advice and suggestions.

Geological Laboratory, University of California, Nov. 1, 1893.

* Since the foregoing was written, the writer's attention has been directed to a paper by Messrs. Fox and Teall (Radiolarian Chert from Mullion Island, Q. J. G. S., Vol. XLIX, 1893, p. 211) in which a "greenstone" showing rolled and ropy masses is described in connection with radiolarian cherts at the Lizard. This occurrence seems to present many interesting parallelisms with that of the Bonita rocks, particularly in regard to the difficulty found in deciding as to the intrusive or surface character of the "greenstone,"—a difficulty which the authors suggest may be removed by supposing the lava to have been intruded between the sheets of the chert, very near the surface of the sea-bed upon which they were being deposited.

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THE POST-PLIOCENE DIASTROPHISM OF THE COAST OF SOUTHERN CALIFORNIA.

BY

ANDREW C. LAWSON.

CONTENTS.

INTRODUCTION.

No clearly defined ideas seem as yet to have been developed in geological literature as to the nature and extent of the diastrophic movements which have affected the coast of California in post-Pliocene time. It is the aim of the present paper to contribute to the development of such ideas, and to enlist, if possible, the interest of geologists in the latest chapter in the geology of the coast. The recency of the record, the vastness of the events, the precision with which they may be established, all contribute to make it the most fascinating as well as perhaps the most important chapter of our local geological history. Nor is its interest of a purely local character. Students of Pleistocene America will profit greatly by a knowledge of the facts so easily ascertained on this coast. The recent evolution of the physiography of the continent has a profound human, as well as a scientific interest. In no part of the continent is the interest so intense as in California. Nowhere is the record so legible; nowhere will greater discoveries reward the researches of the enthusiastic geologist. Yet how few have been the workers in this field! How scant are the opportunities afforded by State aid for systematic research!

The present inquiry is the outcome of studies upon the elevated strands of Carmelo Bay, and the curiosity which was thereby

excited as to the probable extension of these strands along the coast. In order to ascertain the general character of the coast with a view to possible future investigations, a short trip was made from San Francisco to San Diego by steamer, so that, by stopping over at various points, opportunities were secured for an inspection of the coastal topography. Other excursions were also subsequently made by rail. The data obtained are the results of rapid reconnaissance methods. They are, however, of sufficient importance and immediate interest in the judgment of the writer to warrant present publication, notwithstanding the many gaps which could readily be filled by more systematic inquiry. Even with these gaps, the information here given establishes two general facts of no small moment in certain discussions affecting the recent history of the continent. These are:—

1. The uplift or emergence from the sea of the entire coast of California from San Francisco to San Diego, in post-Pliocene time, to an extent of from 800 to 1,500 feet, a very notable epeirogenic event.

2. The local deformation or differential movement of the crust to a very remarkable degree, particularly in the vicinity of Santa Catalina Island and near the city of San Francisco, very notable orogenic events, also of post-Pliocene age.

THE SAN DIEGO MESA.

Physiography.—The county of San Diego comprises portions of three distinct physiographic provinces. These are: (1) The central mountainous range of the Peninsular Sierra, (2) the Colorado Desert on the east, and (3) the coastal slope on the west. This coastal slope is a terraced plain which has a breadth, between the ocean and the mountains, of from twelve to eighteen miles. It is locally known, and commonly spoken of, as "the mesa," the term being applied indiscriminately to the original plateau and to the terraces which have been developed from it. This mesa has been examined cursorily by the writer practically along the entire front of San Diego County, and has been crossed on the line of the San Diego, Cuyamaca and Eastern Railway, and on the branch line of the

Southern California Railway which runs from Oceanside to Escondido. Towards the ocean the lower terraces usually break off abruptly in a vertical sea-cliff above the present strand. Towards the mountains the upper plateau passes in between and behind the outlying isolated peaks and ridges of the range. The contrast in the topography at the line where the plain encircles the mountains is very glaring and impressive. The mountains are bare, jagged masses of white-weathering granite and gneiss, utterly devoid of soil, and sustaining only a very scant shrubbery. The mesa plain presents what is locally a level surface, with no appreciable irregularities to break its surface. Standing on the surface of this plain at its highest part, say near Cajon, or on some of the granite ridges which project through it, the mesa may be seen to extend north and south along the coast as far as the eye can reach. The mountain slopes pass down beneath it and present in a remarkable way the effect of a partially buried topography. As soon as one rises above the level of the plain and looks down upon it, it is discovered that the mesa is dissected by numerous cañons and valleys, through which run the streams from the mountains to the sea. The chief of these streams are the San Diego, the San Diegito, and the San Luis Rey. The streams are the chief agencies which have effected the terracing of the mesa, although true sea-terraces may also in several places be readily discriminated. The mesa with its terraces is being cultivated agriculturally, and as occupation of the land proceeds, and water is brought to it, it will undoubtedly become a rich country.

Structure.—The mesa is genetically a composite Pliocene delta. Structurally it consists of two easily observable portions, viz.: (1) A great thickness of marine sands, generally very light colored, and more or less coherent, passing into sandstone. (2) Above these sands and sandstones a comparatively thin sheet of river gravels of dark appearance, generally somewhat rusty and more or less firmly cemented, so as to constitute a true conglomerate. Mixed with the gravel is much sand and silt. The disintegration of this conglomerate gives rise to the soil of the country, which is well adapted for fruit culture. Over considerable areas the surface is more silty and sandy than gravelly; but the upper sheet of gravel is a character

istic and fairly persistent feature of the mesa. And not only is it found on the upper surface of the old delta plain, but also generally strewn over the different stages of the terraced cañons and valleys, which have been cut down into it. The lower portion is sometimes wanting and the gravel formation rests, as at Point Loma and La Jolla, upon older strata, to which Fairbanks has recently called attention, showing them to be of Cretaceous age.*

Age.—The Pliocene age of the lower portion of the delta is established not only by a comparison of the formations with the characteristic Miocene strata of neighboring portions of the coast, but also by palæontological evidence. Several years ago Dall examined a collection representing sixty-nine species from an excavation at San Diego, and pronounced them to be of Pliocene age.† The formation from which these fossils came appears to be the same as that which underlies the gravels of the greater part of the mesa.

Post-Pliocene marine fossils are also reported by Dall ‡ from the rear of the mesa near San Luis Rey, at an altitude of 600 feet, and twelve miles distant from the shore of the sea. It is not known, however, whether these fossils occur beneath the gravels of the original delta plain, or whether they are found in the formations of one of the earlier terraces which have been cut into the delta.§

Uplift.—The evolution of the greater portion of this delta in Pliocene time was probably a complex process in detail, and no attempt will here be made to enter upon its elucidation. That would require a prolonged study in the field with good maps. But without discussing the conditions which affected the development of the marine

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* Am. Jour. Sci., Vol. XLV., June, 1893, p. 473.

† Proceedings of the California Academy of Sciences, April 7, 1874.

‡ Proceedings of the U. S. National Museum, Vol. I, 1878, p. 3.

§ Dall has recently, in his work on the Neocene (Bull. 84, U. S. G. S., Pl. II), mapped a strip of Miocene along the front of San Diego County. The only warrant for this seems to be an opinion of Conrad's as to the Miocene age of some fossils in a block of sandstone, from an unknown locality, which was handed to Blake in 1853, when he was in the vicinity of San Diego. The present writer saw no formations resembling the characteristic white shale of the Miocene of this coast, and he doubts the presence of the Miocene along the coastal slope of San Diego County. The presence or absence of the Miocene does not, of course, in any way affect the evidence of the Pleistocene uplift discussed in this paper.

portion of the delta, it is perfectly certain that the fluviatile portion—the gravel sheet of the original delta—could only have been developed at base-level, that is, approximately at sea level. The level character of the original gravel sheet indicates a temporarily permanent base-level during the time of its formation; for its extension seaward must have been gradual, the rate depending upon the climatic conditions which controlled the supply of gravel from the innumerable mountain cañons which debouch upon the plain.

This fluviatile gravel sheet of base-level origin is now 800 feet (approximately) above the sea. The rear of the plateau in the vicinity of Cajon, according to barometric observations made by the writer, has an altitude of 790 feet, taking Cajon station, less than half a mile distant and 463 feet above the sea, as a datum. Soledad Mountain, a few miles north-northwest of San Diego, is capped with these gravels, and has an elevation, according to the U. S. Coast and Geodetic Survey, of 810 feet.*

Stream Terraces.—This great delta plain has during the progress of the uplift been successively terraced both by the streams and by the cutting action of littoral forces. Nothing could be plainer to the geological observer than these terraces and their historical significance. No systematic attempt was made by the writer to determine their elevation. The highest stream terraces observed were two on the west side of Cajon Valley, which had altitudes respectively of 675 and 600 feet, the former a broad terrace 200 to 300 yards across, and the latter a narrow terrace. The stream cliffs at the rear of these terraces are still quite steep to climb. From an altitude of 600 feet down to the sea level remnants of stream terraces may be found at many different levels. These terraces are usually abundantly supplied with pebbles and gravel, and in this respect resemble the original delta plain. The method of the development of these gravel-strewn terraces is apparent in the cañons of the present base level. These streams have long since cut down to

* It should be here mentioned, by way of qualification of this coincidence in altitude of the eastern and western edges of the original gravel plain, that the strata of Soledad Mountain have been locally disturbed and slightly tilted, and that there are not lacking suggestions of faulting parallel with the trend of the coast. That this disturbance antedated the general uplift is, however, apparent from the terraces which girtle the hill.

base-level, and are now corrading, forming flat-bottomed valleys with very steep stream-cliffs on either side. Beneath the valley bottoms are the eroded Pliocene or older soft sandstones, but the surface is commonly strewn with pebbles accumulated from the gravels of the upper terraces or the original delta plain, and from the occasional conglomerate beds which are intercalated with the sandstone. Thus, in the stream topography of the coastal slope of San Diego County, there is revealed to the most cursory inspection abundantly demonstrative evidence of a Pleistocene elevation of the coast of 800 feet. The only question which can arise is whether or not this is the full measure of the uplift. The evidence seems to indicate that it is. The wonderfully striking contrast between the bare granite hills and the even plain seems to force upon one the conviction that there are no Pliocene formations above the level of the original gravel plain. It is possible, however, that this assumption may be at fault. If the stationary condition of the coast at which the original delta gravel plain was developed were of very long duration, many times longer than that of the interval since the inception of its uplift, another possibility might obtain.

The marine Pliocene may have been thicker and have buried more of the granite slopes than present appearances suggest, and, being an incoherent sand, have been practically wholly removed down to the level at which the gravel plain was developed. One fact, quite insufficient in itself to warrant any conclusion, but still suggestive, lends support to this possibility. This is the discovery of a few water-worn pebbles on a granite hill near Cajon, at an elevation of 900 feet above tide. Some notches, also, which are observable in the profiles of the granite hills, may possibly be ancient sea-cliffs, but the writer was unable to satisfy himself that such was their origin, since they lack the horizontal extension which characterizes shore features. The writer attaches little weight to these vague suggestions of an uplift exceeding that of which the summit of the gravel plain affords us the measure, and is of the tentative opinion that the demonstrative uplift of 800 feet is the full measure of the Pleistocene uplift of this part of the coast.

Marine Terraces.—Corresponding to the stream terraces are certain well-defined wave-cut terraces. The lower of these are some-

times several hundred yards wide, and may be observed extending parallel to the coast for many miles at several localities between San Diego and the San Luis Rey River. The higher have been observed only on Soledad Mountain, which is marked by a series of wave-cut terraces, with their complementary sea-cliffs, characteristic seaward slope, strictly horizontal scoring of the hillside, and sharp "base-leveling" of the slightly inclined strata. The altitudes of the more prominent of these terraces are about 700, 600, 520, 340, and 160 feet, as determined by aneroid.

SAN PEDRO HILL.

Physiography.—San Pedro Hill is an abruptly projecting, lofty headland of the coast, situated about half way between Point Conception and the Mexican boundary. It is an island-like, rather flat-topped ridge, the trend of which corresponds in general with that of the coast. The base of the hill is surrounded on three sides, the east, south, and west, by the ocean. On the north side a low, sandy tract stretches away from its base, merging into the great plain of Los Angeles. A very moderate depression of the coast, probably not more than 150 feet, would make San Pedro Hill an island. Thus situated, encircled by ocean and low plain, the hill is more closely associated in its physiographic relations with the islands off the coast than with the mainland. The hill may, in fact, as will appear in the sequel, be considered as one of the Channel Islands, which has but recently been reclaimed from the ocean by the uplift of the coast. It is roughly parallel to Santa Catalina and San Clemente, and the three lie in a line and are about equally spaced.

The hill is 1,475 feet high, according to the Coast Survey. It is quite bare of timber and shrubbery, so that its topographical features may be perceived clearly at a glance. The most striking of these features are:—

1. The bold, almost perfectly continuous sea-cliff which encircles the hill above the shore line. This sea-cliff ranges usually from 100 to 200 feet in height. It is frequently over 200 feet, and in one place exceeds 300 feet vertical. The Coast Survey chart shows a broad sub-aqueous shelf, or terrace, continuous with, and complementary to, this cliff, extending out from its base with a gentle seaward slope.

2. The great system of terraces which score the hill like giant steps. All these terraces have steep cliffs at their rear, and several of the steps are of such great dimensions, both vertically and horizontally, that *they appear as prominent features* on the Coast Survey contour map of the hill, scale $\frac{1}{10000}$—a statement which will be appreciated by those who have attempted to give expression to ordinary terraces by means of contours, even on much larger scales. Many of the terraces are, however, of much smaller dimensions, and, although they appeal strongly to the eye, are not expressible on the map.

3. The third prominent topographic feature of the hill to which special attention is drawn is the effect of stream action. The limited catchment area of the hill of course precludes the development of large streams. There are, however, several small streams which flow in the winter season. These would seem to be rather feeble as geological agents, but they have, nevertheless, gashed the hill with numerous sharp cañons, which cut into it across the upper terraces. The lower terraces, below about 240 feet, are not, as a rule, cañoned. The streams from the cañons may in many cases be seen to emerge on the 240-foot terrace, and flow out *over its surface* to the next lower cliff, in a very shallow trench. This next lower cliff is in several instances the cliff of the present strand, and, although where the water falls over it an incipient gorge may be observed, yet the recession of the cliffs is scarcely less rapid than that of the gorge, and in some cases the cliffs are receding so fast that no gorge can be developed. The phenomenon of a stream emerging from a cañon, running out across a terrace, and dropping into a less pronounced cañon in the face of the next lower cliff, is observable on several of the higher terraces also, but it is not so striking a feature as on the 240-foot and lower terraces.* The lesson which the phenomena teach is, of course, the relative topographic youth of the lower part of the hill as compared with the upper part, where the cañons traverse the entire width of the terraces. The cañons are all sharp, *acutely* V-shaped in aspect, and have robbed the hill of but

*This characteristic of the drainage does not hold on the San Pedro Harbor side of the hill, since there it is flanked by newer incoherent formations, which have been easily trenched by the streams.

little of its terraced effect. Even where the cañons are close together, the ridges between them are not sharp, as in the case of older topography, where a different effect, due to the intersection in ridge crests of the slopes of adjoining cañons, is produced. The plateau effect has not yet been destroyed, and the topography of the hill, as a whole, is yet in its juvenescence.

Geological Structure.—San Pedro Hill is composed of the white, siliceous shale which characterizes the Miocene of the coast, together with limestone. Much of the shale is similar to the rocks of the Monterey series at Carmelo Bay.* Certain beds at Redondo beach are rich in siliceous organisms. The dip of the beds at the east end of the hill is westward at an angle of about 22°, and generally over the hill the strata appear to be inclined at angles for the most part not exceeding 30°. Systematic observations were not made for the direction of the dip. The only part of the hill which is not composed of these Miocene rocks is the lower northern and eastern flanks, where Pliocene and later formations have been deposited around its base. These Pliocene formations are rich in fossils, and have attracted the attention of geologists more than the hill itself, so that the Pliocene of San Pedro Harbor is the only Tertiary formation which has been recorded as occurring here.

Evidence of Uplift.—To most geological readers, what has been said of the physiography of San Pedro Hill is in itself sufficient evidence of recent uplift, the inference being that the terraces, which are such striking features of the topography, are sea terraces, and represent ancient ocean strands. That such is the origin of these, and of similar terraces along the coast, has been denied by Mr. George Davidson, of the United States Coast and Geodetic Survey. Mr. Davidson has had exceptionally good opportunities for observation. Although not a professional geologist, his remarks and criticisms are worthy of consideration, and geological science is indebted to him for his keen interest in the terraces as topographic forms, and to the Coast and Geodetic Survey for the many excellent bits of topographic maps which it has given us, of those portions of the coast where the terraces are well displayed. Mr. Davidson not only rejects the idea of the terraces having been developed by the

Cf. this Bulletin, Vol. I, p. 22.

agency of ordinary shore forces, and, therefore, representing ancient shore lines, but advances and argues for the astounding hypothesis that they are due to ice action.*

The present writer interprets the terraces of San Pedro Hill without any hesitation or qualification as marine wave-cut terraces, and exceedingly fine examples of the class. The considerations which establish this interpretation may be briefly outlined.† If the present attitude of the land were to be changed by an uplift of say 100 feet, the shore line would be removed out to the line of the 17 fathom submarine contour, and wave action would there immediately begin the work of evolving a sea-cliff analogous to that of the present strand. As the position of this cliff receded landward, it would become higher and higher. Suppose this process to have continued till the upper edge of the cliff had receded to within one-quarter of a mile of the base of the sea-cliff of the present attitude of the land; we would then have a gently sloping shelf or terrace between two cliffs, one rising from a strictly horizontal line at its rear, and one dropping away abruptly at a line, *not necessarily horizontal*, at its front. But while under our supposed conditions of uplift the lower cliff has been in active recession, and kept near the vertical by the constant cutting of the waves at its base, the upper cliff has been exposed to atmospheric erosion, and has, therefore, lost something of its vertical and abrupt character. It has been softened down by rounding of its upper edge and by the accumulation of alluvium at its base. The surface of the terrace, when lifted above the water, was strewn with (1) water-worn bowlders and pebbles chiefly accumulated in the bays, and (2) marine organisms; both plant and animal. The bowlders and pebbles, having resisted the attrition of the shore action, would endure for a long time. The soft parts of the plants and animals would rapidly disappear; and later the calcareous shells and other hard parts, being exposed at the surface, would, for the most part, be dissolved and

* For Mr. Davidson's views in detail, see his paper, "The Abrasions of the Continental Shores of Northwest America, and the Supposed Ancient Sea Levels," Proceedings of the California Academy of Sciences, May 5, 1873.

† Mr. Davidson says, "The upheaval of the continental shores by subterranean action cannot produce such terraces and plateaus. . . . The action of water will not account for them." *Loc. cit.*

disappear, but the marks of the boring mollusks would remain, to testify to their former presence. Locally, also, owing to certain special conditions, the lower cliff might have receded so rapidly as to entirely obliterate the terrace. The lower and upper cliffs would then appear as one, and, as a single cliff, might have encroached upon the land beyond our elevated shore line.* Thus we have before us the characteristics of the sea terrace which would be presented for inspection if the present shore line were to be elevated 100 feet, viz., a narrow plateau-like shelf, gently sloping seaward, limited in the rear by a strictly horizontal line (the shore line), above which would rise a somewhat softened sea-cliff 100 to 200 feet, and in one place 300 feet, high, and limited in front by a more vertical cliff rising above the new shore line. On this shelf would be strewn bowlders and pebbles, chiefly in the embayments, and in the soft, fine-grained rock of which the hill is composed mollusk borings would abound. Had the rock been hard or unequally resistant, occasional, conical stacks would rise above the otherwise even slope of the terrace. Precisely these features characterize the terraces which score the slopes of San Pedro Hill so notably. Every terrace is a shelf cut into the rocky slope, beveling the upturned edges of the strata. Every terrace has a cliff rising steeply from its rear, the intersection of the plane of the terrace and that of the cliff being a strictly horizontal line, as near as the eye can judge. Every terrace falls away with varying degrees of definiteness into the cliff of the next terrace below. Every terrace has a gentle seaward slope, which is inherent in its rocky floor, and not due essentially to alluvium. The terraces are strewn sparingly with pebbles and water-worn bowlders of moderate size. Mollusk borings are plentiful, and were observed by the writer on several of the terraces up to an elevation of 1,240 feet above sea level. Terraces having these characters are clearly ancient ocean strands, and the suggestion that they are due to the abrasion of moving ice is, therefore, absolutely negatived.

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* For a fuller account of the development of sea-cliffs and other shore features, consult Gilbert's "Lake Bonneville," U. S. G. S. Monograph I. It should be noted, however, that certain features associated with the development of sea-cliffs, and given by Gilbert as criteria for the recognition of sea-cliffs of lakes, are, as a rule, not available for this purpose on oceanic coasts.

These strands were identified by the writer at the following approximate altitudes, viz.:—1,240, 1,040, 960, 860, 700, 550, 400, 300, 240, 160 and 120 feet.

The figures are given for the shore lines at the rear of the terraces or the base of the sea-cliffs. Since the terraces are, in many cases, quite broad (one-quarter of a mile and more), these figures are higher than those given for the same terraces by Mr. Davidson,* who seems to have given the altitude for some point on the slope of the terraces considerably below the horizontal line which marks their abutment against the cliffs.

Exceptional interest centers, of course, upon the highest terrace of the series, since it affords us the measure of the total observable uplift. This terrace, at 1,240 feet, is fortunately well supplied with water-worn pebbles and mollusk borings in the limestone, so that as a shore line its character is, like Cæsar's wife, above suspicion. The altitude of San Pedro Hill is given by the Coast Survey at 1,475 feet, but between the 1,240-foot terrace and the summit no evidences of shore action could be observed, and the suggestion from the facts is that 1,240 feet is the full measure of the uplift on this part of the coast. It is possible, however, that San Pedro Hill may have been completely submerged at a stage of the depression of the coast of which we have here no record. It is also possible that more careful and prolonged search than the writer had time for, may in future result in the discovery of traces of shore action between the 1,240-foot terrace and the summit of this hill.

The Record of Geological Events.—The facts observable at San Pedro Hill warrant certain general conclusions, having a high degree of probability as to the sequence of events on the coast in late Tertiary and Pleistocene times. It is clear that San Pedro Hill was, during the greater part of the process of the uplift, an island of the Pacific. That is, it was a hill or isolated ridge which had earlier been depressed till it was almost entirely, or possibly entirely, submerged. This hill, giving due weight to the possibility of its being essentially of structural origin, was undoubtedly shaped by ordinary stream and atmospheric erosion. The rocks composing the hill being of Miocene age and the lower flanks of the hill being mantled

* *Loc. cit.*

by Pliocene formations, this epoch of erosion must have been the same as that which is generally recognized in California geology as the post-Miocene uplift. There thus appears to have been an important interval of denudation between the Miocene uplift and the depression which permitted the deposition on the lower flanks of the hill of the formations which paleontologists recognize as of Pliocene age.* The recovery from this Pliocene depression is the uplift which is registered in the elevated strands of the hill. The Pliocene strata were probably deposited at an early stage of the depression, and were slightly deformed by movements which affected the coast, or by local causes, and were subsequently truncated and terraced when again brought within range of wave action by the uplift at its later stages. The Pleistocene strata which overlie the Pliocene doubtless also belong to a recent stage of the uplift. It follows that, while there is a very profound physical break between the Miocene and Pliocene, the marine Pliocene and Pleistocene formations are intimately associated, with no epoch of subaërial denudation between them.

SAN CLEMENTE ISLAND.

Physiography.—If we disregard the Los Coronados group of rocks, which lie off the Mexican coast, San Clemente is the most southerly of the Channel Islands of Southern California. It is situated at a distance of about fifty-seven miles from the mainland. Its southern extremity is but little north of east of San Diego, and is due south of San Pedro Hill. The island is long in proportion to its width, and its longer axis has a northwest and southeast trend, being parallel to the opposite shore of the mainland. Its length is twenty-one miles. The southeast third of the island has a breadth of four miles, while the remaining two-thirds tapers towards its northwestern extremity, where it is only a mile across.

The topographic features of the island are simple, yet of an exceedingly severe cast. Bare of timber and supporting besides grass only a scant shrubbery and various varieties of cacti, the relief

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* Dall's statement of the Neocene (probably Pliocene) age of the middle stratum of Deadman's Island, taken in connection with the writer's stratigraphical observations, is the warrant for the identification of the Pliocene at San Pedro Harbor. *Cf.* Bull. 84, U. S. G. S., p. 216 and map, Pl. II.

stands out in bold lines, sharp, yet massive and impressive. The shore contour exemplifies this simplicity in a remarkable degree, being devoid alike of sinuous bays and of intricate coves, so that practically there are no sheltered harbors, even for small craft, on the island, the only anchorages being a few roadsteads very close to shore. The island is essentially a flat-topped, plateau-like ridge, the crest of which runs along the northeast side of the island, having a maximum elevation of 1,964 feet. This side presents a wonderfully abrupt and precipitous scarp, rising sharply from the ocean level to elevations ranging from a few hundred feet to 1,800 feet in sheer acclivity. From the crest line the surface descends, partly by gentle slopes and partly by abrupt, step-like terraces, to the southwest shore of the island, the present sea-cliffs along this side being of very moderate elevation. The transverse profile of the island is thus similar to that of a tilted orographic block. This suggestion as to the orographic structure of the island is supported by the occurrence of fault scarps of smaller dimensions on the surface of the island parallel to its general trend, at a point about one-third of its length from the north end, and to the east of the crest trail. It is the opinion of the writer that the precipitous northeast scarp of San Clemente is genetically a fault scarp, although it is now, and has been at many lower stages of the island, functionally a sea-cliff. The submarine contours show that the contrast of slope on the two sides of the island is maintained beneath the shore contour.

The imposing feature of the topography is, however, the system of wave-wrought terraces which have been cut with such wonderful vigor and incisiveness into the slopes of the island, particularly on its southwest side. These terraces are the most remarkable and most magnificent examples of this type of topography which it has ever been the good fortune of the writer to behold. Up to an elevation of 1,320 feet there are seventeen great terraces which appear to be of amazingly recent formation, so little has atmospheric degradation affected them, with such precision do they retain their original characters. Such features having once been evolved, one might expect to find on a planet that had been stripped of its atmosphere, where erosion is not, and topographic forms have become fixed, no longer the geologically evanescent things we know them to be on

this earth. These terraces have but a very scant soil or are bare rock, and the cliffs which rise abruptly from the horizontal line at their rear are commonly beetling crags, so steep as only to be clambered over with great difficulty and at favorable places, while in many places they cannot be scaled. The slope of the terraces is always seaward at a low angle, and upon the rocky floors there may be observed occasional isolated conical crags, rising twenty, thirty, forty, or fifty feet above the terrace at some distance out from the base of the cliff, precisely analogous to the "stacks" which project through the surf from the littoral shelf of to-day. The breadth of these great terraces ranges commonly from 200 to 1,500 feet, and the height of their cliffs from 50 or 60 to 300 feet. Water-worn pebbles are sparingly strewn over the surface of the terraces, but probably not more sparingly than along the present strand, where water-worn pebbles and bowlders are only abundant at exceptional localities, such as Seal Cove, where the shore drift lodges and accumulates. It is frequently obvious that the excessive recession of some of the sea-cliffs has resulted locally in the obliteration of one or more terraces above them, so that the plots of transverse profiles, at half-mile intervals, say, would show many important discrepancies, owing to the dropping out of a certain terrace in this profile, two other terraces in that, and so on. The extent and breadth of the terraces, and the vertical dimensions of their sea-cliffs, are so great that they appear as very striking features on the United States Coast and Geodetic Survey's manuscript map of the island, scale $\frac{1}{10000}$, contour interval forty feet. But, although the terraces and cliffs are very apparent on the map, it is not possible to read off, with even approximate precision, the altitude of the base of the cliffs, owing to the large vertical interval employed in the contours.*

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*In 1863 Dr. Cooper, as zoölogist to the Geological Survey, visited San Clemente, observed the terraces and appreciated their significance. His observations are given by Whitney in the "Geology of California," Vol. 1, p. 184. He says: "Its form is that of a terraced table; and although from the nature of the rock and the scarcity of shells but very few fossils have been preserved, yet there is sufficient evidence that each one of the terraces, of which there are about seven, has been at one time the beach of the island. . . . The elevation of the highest terrace was estimated at 1,000 feet." This brief statement

Besides these great terraces, which contour the southwest side of the island up to an altitude of 1,320 feet, there are observable in other parts of the island, particularly along the gentle longitudinal slope from Wilson's Cove to the summit, many less prominent terraces occupying the same vertical interval. On this trail there were observed no less than eighteen distinct terraces, two of them exceeding in elevation the 1,320-foot terrace. The altitudes of the terraces at the rear are given in the following table:—

Altitudes of terraces, as determined by aneroid on trail from Wilson's Cove to the summit.	Altitudes of terraces on S. W. side of island, as read from Coast Survey MS. map, to the nearest 40-ft. contour.
1,500 feet.	
1,375 "	
	1,320 feet.
1,250 "	1,240 "
1,040 "	1,040 "
960 "	960 "
930 "	
785 "	800 "
	680 "
580 "	
550 "	560 "
470 "	480 "
	440 "
380 "	400 "
325 "	320 "
	280 "
225 "	200 "
170 "	160 "
120 "	120 "
85 "	80 "
40 "	40 "
12 "	

given at second hand is the most valuable and authentic information on record of perhaps the most important geological event on the coast of California since the post-Miocene uplift. Dr. Cooper's observations have met with but scant courtesy from geologists, and the correctness of his interpretations has been doubted ever since the appearance of Mr. Davidson's paper, above referred to, in which the origin of the terraces was ascribed to ice action. The present writer verifies Dr. Cooper's observations and conclusions and extends them.

The two highest terraces seem to be much older than those on the southwest side of the island, from 1,320 feet down. Their sea-cliffs are much more degraded, so that, although the terrace line is a well-marked feature of the landscape when viewed from a distance, the sharpness of the contrast between the cliff slope and the terrace slope is not so apparent to the observer when he is on the immediate ground. There is, however, no reasonable doubt as to their being sea terraces, as the beveled edges of the inclined strata of the terrace floors and the horizontality of the rear amply testify to their origin. Above the highest observed terrace, at 1,500 feet to the summit of the island (1,964 feet), the topography has a non-terraced aspect. This may possibly, of course, be due to the greater age of the topography, terraces once existent having disappeared.

The stream topography of the island is in harmony with the character of the terraces. Streams are few, and it is very evident that they have but begun their work of sculpture. On the upper plateau of the island the drainage runs in open swails with shallow trenches. In their descent over the great cliffs and terraces of the southwest side of the island, however, the streams have cut sharp, deep, steep-walled cañons into the rocky floors. In the case of the middle portions of the cañons their abruptness and narrowness constantly excite the surprise of the explorer. In walking along on the rocky floor of a terrace, the trench will often scarcely be perceived till the brink is reached, and its gloomy depths yawn vertically beneath one's feet. Their narrowness and straightness give them the effect of saw cuts across the terraces rather than of stream courses. In their upper portions they are a little more open and V-shaped, while in their lower parts the streams have in many cases made but very moderate incisions into the more recently elevated terraces. In no case are the streams at base-level. Besides these streams which descend from the upper plateau, trenching the whole system of terraces, and therefore antecedent to the last thousand feet of uplift, there are numerous other minor water courses which are consequent upon the uplift, having their sources in the various ancient sea-cliffs. These have a much smaller share of the rainfall to carry off, and their work is correspondingly less important; but still they have in many cases made considerable headway in

cutting gorges back across the terraces of medium altitude. On the lower terraces these minor water courses flow over the surface in very shallow trenches.

Thus the results of stream action, like the character of the terraces, testify abundantly to the youth of the topography of San Clemente and to the recency of its emergency from the waters of the Pacific.

The Rocks of San Clemente.—From what has been said of the physiography of San Clemente Island it will be apparent that in its main features it resembles San Pedro Hill. The difference in the two cases lies chiefly in the stronger accentuation of the relief on San Clemente. Notwithstanding this similarity of topography, the rocky substructure of San Clemente is totally different from that of San Pedro Hill. Instead of the rather soft, white, siliceous shale of which the latter is composed, San Clemente is built up of volcanic lavas with some intercalated volcanic breccias, and a very limited proportion of fossiliferous, white limestone, which may be the equivalent of the Miocene of the coast. These limestones are seen at Wilson's Cove, where they are fossiliferous and repose in a disturbed condition upon the volcanic beds. The latter are thus apparently of not later age than Miocene. They appear to be mostly basalts, more or less vesicular, with lighter colored rocks of rather open texture, which are probably andesites. The bedding of the volcanic flows is usually more or less distinct, and is generally inclined, so that the terraces bevel their edges. Observations sufficient to warrant a statement as to the stratigraphical structure of the island were not attempted. The general impression was obtained, however, that on the southwest side of the island the dip was to the southwest. On the cliffs and stream cañons of this side of the island there are numerous caves and cavernous recesses. These appear to be an original characteristic of the lava flows, and are only *exposed*, *not formed*, by erosive agencies. An important lesson is learned from a comparison of the geological character of San Clemente Island with that of San Pedro Hill, viz., that within certain limits the forces which have been active in the formation of the great terraces, as well as the forces of subaërial erosion which tend to their destruction, have effected the same result, practically

independently of the petrographical character of the mass operated upon. The bearing of this will be apparent when we come to consider the case of Santa Catalina Island.

Uplift.—The description of the physiographic features of San Clemente will leave no doubt in the mind of the appreciative reader as to the interpretation which is to be placed upon the terraces of the island. They are unquestionably sea terraces, and represent elevated ocean strands. The character of the terraces indicates that the uplift progressed by stages, and that many of these stages represent a long-continued practical permanency of the relations of land and sea. There is no implication, however, that the passage from stage to stage was *per saltum.* The change from one stage to another was probably gradual, and it is entirely compatible with the results now observable that the actual progress of the uplift from stage to stage was very slow. The full number of these stages is probably greater than is now registered in the elevated strands of the island, and many more strands remain to be discovered by more careful examinations in future. No less than twenty-two strands have, however, been recognized, as stated on a previous page. These doubtless have very different values as regards the time occupied in the recession of their respective sea-cliffs, the breadth of the several terraces varying greatly. The partial obliteration of most of the terraces, by the recession of the later cliffs below them, prevents our obtaining any correct figures for the amount of horizontal cutting done at any given stage, or for the total amount of cutting done at all stages. That some general idea, however, of the work done by the waves during the uplift of the island might be given, the writer has measured the maximum widths of seventeen prominent terraces shown on the Coast Survey map, and finds that their sum is about two miles. Some of the outer portions of a few of these terraces may, possibly, be slopes not properly to be regarded as wave-cut, but the majority of them are but the remnants of once much broader wave-cut terraces, which have been reduced by the encroachment of cliffs of later stages of the uplift. Two miles is, therefore, far within the minimum value of the total amount of horizontal sawing which has been effected in the slopes of the island by wave action during its elevation through the last 1,320 feet. If we

knew the rate of recession of the cliffs, we might from this data acquire a minimum value for the time occupied in the uplift.

In comparing the figures obtained for the altitudes of the ancient strands of San Pedro Hill with those of San Clemente, the interesting and suggestive fact comes out that the highest three terraces of the former series have exact hypsometric equivalents in the latter, and that most of the other lower terraces of San Pedro Hill seem also to have their strict equivalents on the island. The suggestion is that the hill and the island have emerged from the sea in unison, at the same rate, by the same stages. The facts to be narrated concerning Santa Catalina Island tend, however, to discredit this suggestion, as will appear in the sequel.

SANTA CATALINA ISLAND.

Compared with San Pedro Hill and San Clemente.—In all the physiographic wonderland of Southern California there is probably nothing more surprising than the contrast which the topography of Santa Catalina presents to that of both San Pedro Hill and San Clemente. Lying midway between the two latter insular masses, in the same physiographic province, and affected by the same climatic conditions, Santa Catalina might, *a priori*, be supposed to differ from these but little in the character of its land sculpture. This supposition proves, however, to be fallacious. The difference between the aspect of the island and that of the two other neighboring insular masses is amazing, and the hypothesis which we are forced to entertain to account for it, is correspondingly startling.

The island has almost exactly the same length as San Clemente, and has about the same trend. The greatest width is, however, twice that of San Clemente. Its summit is 2,109 feet above the sea, or only 145 feet higher than that of the sister island. The writer had an opportunity of inspecting the topography of the island under unexceptional conditions, while circumnavigating it in a naphtha launch, within easy reach of shore, in calm, clear weather. All parts of the island were thus passed in critical review. Bearing in mind the account which has been given of San Pedro Hill and San Clemente, the following brief statements will suffice to make clear those fea-

tures of the island which, from a comparative point of view, are most remarkable and significant:—

1. There is no trace of an elevated wave-cut terrace, sea-cliff, or strand line of any kind observable on the island.

2. The stream topography of the island is very much more advanced, *i. e.*, much more ancient than that of either San Pedro Hill or San Clemente.

3. The island is almost cut into two parts by a low pass (less than twenty feet above tide), which can only be regarded as of the nature of a stream-eroded valley. The smaller of these two parts has an altitude of 1,783 feet, the larger an altitude, as above stated, of 2,109 feet.

Absence of Elevated Strands.—The entire absence of evidence of the former occupation of the slopes of the island by oceanic strands, indicates clearly that Santa Catalina has not been subjected to the same process of emergence from the ocean which is so abundantly demonstrated for both San Pedro Hill and San Clemente. It is incredible that, having been subjected to the same uplift, under the same conditions of exposure to wave action, similar terraces should not have been formed. The only condition which might be invoked to differentiate Santa Catalina from San Pedro Hill and San Clemente is the petrographical character of the island, which is not uniform. The larger part of the island is, however, composed of volcanic rocks not essentially different in their general field character from those of San Clemente, and, although at the western end of the island, the underlying pre-volcanic strata appear, their susceptibility to sculpture by wave action cannot be to any practical extent less than that of the rocks of San Clemente. It has been shown, moreover, that the processes of shore action and of subsequent degradation have left us a terraced topography on both San Pedro Hill and San Clemente which is practically independent of the petrographical character of those two land masses. The powerful nature of oceanic shore forces belittles the effect of slight petrographical differences in the material against which they are directed. It thus seems certain that had this island emerged from the sea *pari passu* with either San Pedro or San Clemente, or with both, it must have been similarly terraced. It is equally incredible that the terraces, once having

been formed, should have been completely obliterated, while those of San Pedro Hill and San Clemente, under the same climatic conditions, should remain so magnificently perfect in their profiles.

The inference from the absence of elevated strand lines is irresistible. Santa Catalina has not been subjected to the uplift which has affected the two prominent insular masses, one twenty-five miles to the north of it and the other twenty-five miles to the south of it.

More Ancient Stream Topography.—The stream topography of the island testifies with equal force to the truth of this conclusion, and the evidence which it offers is positive, direct, and unavoidable. San Pedro Hill and San Clemente have both been shown to be terraced plateau-like ridges, upon which stream action has as yet produced but little degrading effect. On Santa Catalina it is far otherwise. The degradation of the island is well advanced, and the original form of the mass upon which the streams first began to operate, is no longer discernible. On San Pedro Hill and San Clemente the stream trenches are comparatively few in number, and are exceedingly sharp and precipitous narrow gorges, generally separated from one another by stretches of terrace flats. On Santa Catalina the trenches are very numerous and are wide-open V-shaped cañons. The catchment areas of these cañons are separated from one another by sharp sloping ridges, formed by the intersection of adjacent cañon slopes. The entire island may be described as a continuous alternation of cañons and their separating ridges, there being practically no plateau land remaining. None of the streams are at base-level, but, on the contrary, have the high grade character of mountain drainage. From this it will be evident that the topography of the island is by no means *ancient*, as geologists usually apply the word to stream topography. It is only the contrast with the very much more youthful topography of San Pedro Hill and San Clemente which justifies the use of the term. The relative age of streams, near their headwaters in mountain ridges, is to be measured by the mass of the mountain which they have removed, for, although the streams be very ancient and endure through succeeding geological periods, the topography at their head-waters will always have the "youthful" character, till the mountain is obliterated. In this sense the streams of Santa Catalina may be more ancient than many

a river meandering through a base-level plain in a region of very "ancient" and "mature" topography. In this sense they are certainly *very* ancient compared with those of San Pedro Hill and San Clemente, for the amount of degradation of the land is many hundred fold that which has been effected in the case of these two masses. (See Plate 8.)

It thus appears that Santa Catalina was a land mass, subject to the forces of subaërial degradation, at the time when San Pedro Hill and San Clemente began to emerge from beneath the waters of the Pacific, in post-Pliocene time.

Evidence of Subsidence.—Nor is this the end of our deduction. An additional probability presents itself. The island seems to have been subjected to a process of submergence which may even now be active.* The emergence of land from beneath the waters of the ocean is usually easy to detect, as has been exemplified in the case of San Pedro Hill and San Clemente. The fact of submergence is more difficult of recognition. Two chief characteristics of a subsiding coast are (1) the flooding of stream valleys and the consequent formation of harbors, and (2) the more rapid recession of the sea-cliffs than in the case of a stationary or rising coast.† Both of these conditions seem to be fulfilled in the case of Santa Catalina Island. The low pass which almost bisects the island at the "Isthmus," and the flooded portion of which forms the excellent shelter known as Catalina Harbor, is almost beyond question a stream gorge. The highest part of this pass is now less than 20 feet above tide, and the hills rise abruptly on either side. As a stream gorge it could not have been evolved at the present relative attitude of land and sea. The gorge is almost completely submerged. The conditions are, to say the least, strongly suggestive of a submergence of the island.

The argument from the sea-cliffs is not less forcible. Except at one place near the south end of the island the sea-cliffs are not remarkable for their height. They lack the continuity which marks

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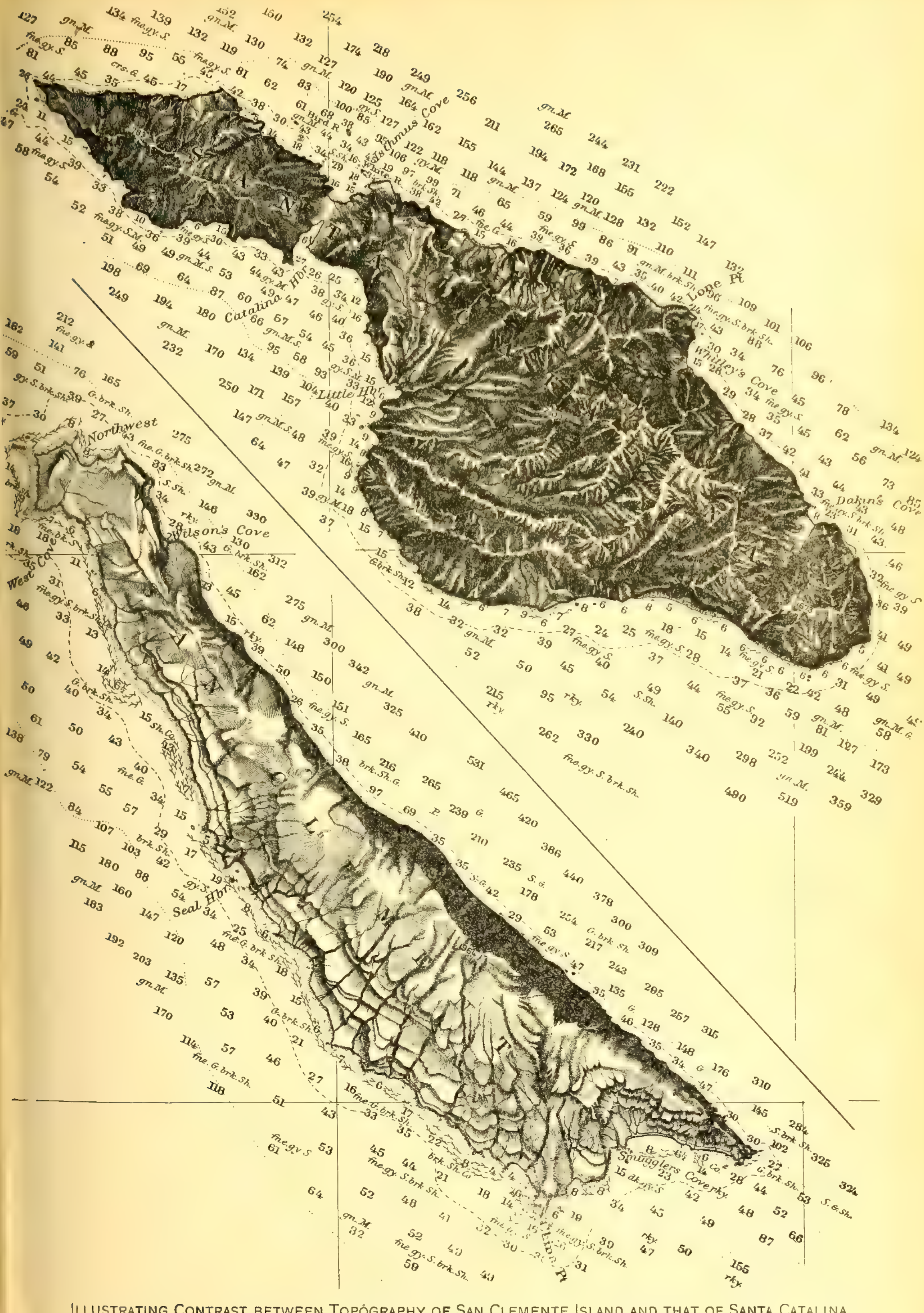
*Dr. Cooper, in his visit to these islands in 1863, noted the absence of terraces on Santa Catalina, and surmised that it might be sinking. "Geology of California." Vol. I, p. 185.

†See Gilbert, Lake Bonneville, U. S. G. S., Monograph I, p. 73.



Illustrating Contrast between Topography of San Clemente Island and that of Santa Catalina

Reproduced from C. and G. S. Chart. Scale $\frac{1}{200,000}$.

the sea-cliffs of San Pedro and San Clemente. Their excessively rapid recession is shown in their relation to the cañons of the island. Where the sea-cliffs cut across the mouth of a cañon, it is frequently apparent, particularly on the southwest side of the island, that the recession of the cliff has been much more rapid than the rate at which the streams can sink their trenches or cut back their gorges. This results in a topographic phenomenon not observed by the writer anywhere else on the California coast. The valley or cañon bottoms, instead of sloping to the sea level, end abruptly at the brink of a sheer cliff, over which the stream falls 30, 50, 80, or 100 feet, etc., as the case may be, without any serious pretense of a stream-cut gorge in the face of the cliff. This can only be due to an excessively rapid recession of the sea-cliffs relatively to the trenching of the cañons. And in this fact we have again evidence that Santa Catalina Island is sinking beneath the waters of the Pacific. What is the measure of the depression which has already been effected?—Twenty-five miles to the north San Pedro Hill has been demonstrated to have participated in an uplift of at least 1,240 feet. Twenty-five miles to the south San Clemente has risen from the ocean through 1,500 feet. What relation exists between the depression of Santa Catalina and the uplift on either side? The answer to this question can only be a tentative or speculative one. The facts, however, strange as they appear, may be readily verified, and are not more wonderful than many other, perhaps less patent, but still indubitable phenomena of a like kind which may be read in the physiography of Southern California.

CARMELO BAY.

In a former paper* the writer has shown that in the vicinity of Carmelo Bay there is abundant evidence of the recent elevation of the coast to an extent of at least 800 feet. The evidence is of the same character as that described in the present paper for other parts of the coast. Although no evidence of uplift exceeding 800 feet was observed within the limits of the area then examined and described, it is very probable that on the high ground back of Carmelo Bay still higher strand lines will be found.

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*This Bull., p. 46, *et. seq.*

THE SANTA CRUZ TERRACES.

The coast of the Bay of Monterey, in the vicinity of the town of Santa Cruz, and for about fifteen miles to the west-northwest of it, is very beautifully terraced. The terraces are seen to best advantage when one approaches Santa Cruz by water. From shipboard three great terraces may be observed extending continuously for the distance mentioned, while near the town a fourth terrace of limited extent appears between the upper two. The strict horizontality of these terraces, as they are viewed in their entire extent from a favorable position off shore, is perhaps their most impressive feature to the casual observer. Examined at close quarters, these four terraces are found to have altitudes respectively of 96, 205, 374, and 712 feet at their rear.* They have steep sea-cliffs, with horizontal base, and their gentle seaward slope is sparingly strewn with shore-worn pebbles. The terraces are entirely wave-cut, carved out of the rocky slope. The coast is occupied by the white, siliceous, Miocene shales, with some sandstones, reposing upon the worn surface of a complex of altered sedimentary rocks, and crystalline limestone, invaded by the granite of the Santa Cruz Range.

The Miocene strata occupy a strip between the shore and the granite and dip away from the latter at low angles beneath the waters of the bay. The lowest, or ninety-six-foot terrace, is very broad near the town, ranging from half a mile to over a mile in width. Its slope, although in the same direction as the dip of the shales, is at a lower angle, so that, in the many cañon sections which may be observed, the truncation or "base leveling" of the slightly inclined strata is very beautifully displayed, and is a feature of the terrace from its rear down to the brink of the present sea cliff. At the rear of this terrace may be observed, also, many instances of the phenomenon noted at San Pedro Hill, of water-worn ravines cut down in the hill behind the terrace to the level of its rear, *but no*

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*Whitney mentions "two well-marked terraces" at Santa Cruz, and gives their altitudes as 64 feet and 263 feet; but it is improbable that these figures are for the rear of the terraces. The higher terraces here described escaped the observation of the officers of the Geological Survey, and are now recorded for the first time. *Cf.* "Geology of California," Vol. I, page 165.

deeper. They were thus developed when the rear of the terrace was at base level, and since the uplift they have not had time to lower their trench into the new terrace. The drainage from these ravines runs out over the surface of the terrace, and has in each case inaugurated a gorge which is heading back from the present sea-cliff toward the source of the stream. This state of affairs characterizes only the small water courses. The larger streams, which come from the mountains, and which are antecedent to the uplift, have effectually trenched the terrace.

The second terrace is also a broad one, and cuts into the same shale. Its maximum width is, however, less than half a mile, and generally the terrace does not exceed a quarter of a mile across. The bevelment of the slightly inclined strata at the surface of the terrace is here again well displayed in many sections. The higher terraces are cut partly in the shale and partly in the complex of metamorphic rocks and granite which rises from beneath it. The granite is generally more or less decomposed. The metamorphic rocks are, however, hard and fresh. The limestone has the character of a coarse marble. In addition to the terraces which are so apparent from shipboard off the coast, there are several others of higher elevation which are more or less obscured by the shrubbery and trees which flourish on the upper slopes. These are all strewn with shore drift, usually in the form of small, water-worn pebbles, and occasionally, on the highest terraces, these pebbles are aggregated and cemented together to form a conglomerate of local extent. An effort was made to ascertain the altitude of the various terraces examined by means of a mercurial barometer. The following figures were thus obtained, the point of observation being in each case the rear of the terrace where it abuts upon its sea-cliff. The only exception to this is in the case of the highest terrace, where on the line of our examination a stream has cut back so as to have carried away the rear portion of the terrace. The figures for this terrace may, therefore, be a little lower than the true altitude of the strand line. The altitudes are 1,201, 1,133, 1,025, 969, 871, 712, 374, 205, and 96 feet above tide.

Above the 1,201-foot terrace there are no traces of any kind of shore action, and the slopes rise ruggedly for several hundred feet

to the brink of a gently undulating plateau, the significance of the topography of which has not been investigated. In studying these terraces the ground has been visited several times; but in determining their altitude a single favorable line was followed, and it is not supposed that the list of altitudes here given represents all of the terraces which score the coastal slope. In several instances it is very apparent that the terraces are discontinuous, owing to their having been locally obliterated by the excessive recession of the sea-cliff of a later stage of the uplift. For this reason parallel profiles do not always show the same number of terraces with the same intervals; and other strand lines may exist than those here recorded. It is even possible that the highest observed strand, at 1,201 feet, may not be the highest discoverable on this part of the coast, although locally there is no suggestion of any higher strand line.

It is probable that the topography of the valleys of the antecedent streams which come down from the Santa Cruz Mountains may be definitely correlated with the terraces, *i. e.*, with the different stages of the uplift. This is certainly possible as regards some of the features of the San Lorenzo, which has a sharp V-shaped gorge for about five miles back from Santa Cruz, cutting through the shale and the underlying granite. At this point, above the breast of the gorge, the valley opens out and clearly represents the topography established when the stream was at base-level and had time for corrasion. This broader valley bottom is over three hundred feet above sea level; and the five-mile gorge, largely through granite, is the measure of the time, since the initiation of its uplift.

THE MERCED SERIES.

General Note.—The most remarkable development of Pliocene rocks in North America is on the Peninsula of San Francisco, a few miles south of the Golden Gate. The remarkable features are; (1) The great thickness of continuous sedimentation which it represents, and (2) the local disturbance to which it has been subjected. Both of these features are observable and quantitatively determinable in the magnificent line of sea-cliff which extends from Lake Merced, near San Francisco, to Mussel Rock, about eight miles south of Point Lobos, at the entrance to the gate. For convenience the Pli-

ocene rocks here referred to will be designated the *Merced series* from Lake Merced, which lies in a structural or synclinal depression of the Pliocene terrane, to the south of the city. The base of the Merced series is observable at Mussel Rock. The basal bed is a stratum of partially carbonized forest material, from which fragments of little altered wood, bark, branches, matted leaves, and pine cones may be gathered *ad libitum.* The cones, according to Prof. E. L. Greene, who kindly examined them for me, are those of *Pinus insignis* (Monterey pine), a tree which at the present time grows only at Monterey. The forest bed rests directly on a seemingly even surface of volcanic rocks (pyroclastic and massive) which are of Mesozoic age. This surface slopes now to the north at an angle of 15°. It is a surface of truncation by erosion and doubtless represents a pre-Pliocene base-leveled plain.

From this basement at Mussel Rock the strata of the Merced series are well exposed in ascending sequence to Lake Merced. The edges of the strata form the sea-cliff for the entire distance. The sea-cliff is in active recession, so that fresh exposures of the rocks are afforded throughout the section. The strike is for the most part more or less transverse to the shore, and the latter is a simple, nearly straight line. The rocks are tilted, generally at high angles, and have a monoclinal structure for the entire length of the section. The sharpness of the strata and the comparative constancy of both dip and strike favor precise observation. There is no repetition of strata, and fault structure is represented only by very minor dislocations. In a word, the section is ideally simple, and is eminently susceptible of approximately accurate measurement for the thickness of the series. There is but one drawback, and that consists of the two land slides which scar the face of the cliff. These, however, do not practically affect the results set forth in the sequel, since one occurs where the strike is locally parallel to the line of section, and is therefore not considered in the calculation, while the other, near Mussel Rock, although not showing the strata in the sea-cliff, shows them in the cliff behind the slide. The cliff at its highest is about 720 feet above the shore, and at several places the strata may be seen extending from the shore to the top of the cliff with uniform dip. The rocks are chiefly soft sandstones of gray

color, often argillaceous and passing into sandy shales. Interbedded with these are frequent hard, well-cemented shell beds, and hard beds of pebbly conglomerate. Shell beds also occur in a soft condition both sandy and clayey. There are besides these occasional thin lignitic seams, and toward the north end of the section there is a thin bed of white volcanic ash. The stratification is usually very clearly and sharply marked.

Fossils.—The series abounds in Pliocene fossils both in this particular section and in other parts of the terrane. Dr. J. G. Cooper lists the following species from this cliff section in his "Cataolgue of Californian Fossils," 1888:—

Arca microdonta Conr. Pl.
*Chione succinta Val. Pl.
Crepidula grandis Midd. Pl.
Columbella Richthofeni Gabb Pl.
*Nassa fossata Gld. Pl.
*Olivella biplicata Sby. Pl.
*Purpura crispata Chem. Var. septentrionalis Rve. Pl.
*Standella falcata Gld. Pl.
*Echinarachnius excentricus Esch. Pl.
Scutella interlineata Stimp. Pl.

The following additional forms have been collected by the writer, and by him submitted to Dr. W. H. Dall, who has kindly identified them:—

*Nassa mendica Gld.
*Macoma (like sabulosa Spngl.)
*Macoma nasuta Conr.
*Chrysodomus lyratus Mart.
*Monoceros engonatum Conr.
*Astyris gausapata Gld.
Crepidula prærupta.
*Schizothærus Nuttallii Conr.
*Siliqua patula Dixon.
*Mytilus edulis L.
*Venericardia ventricosa Gld.
Mactra sp.
Oyster sp.

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* Still living.

Besides these, Mr. W. J. Raymond, of the University of California, has kindly placed at the writer's disposal the following list of fossils, which he has collected from the same section, and identified:—

*Saxidomus gracilis Gld.
Tapes Staleyi Gabb.
*Natica Lewisii Gld.
*Solen sicarius Gld.

In the same series Dr. Cooper records the occurrence of the following species in the vicinity of the Twelve Mile House and Twelve Mile Creek, a few miles to the eastward of Mussel Rock:—

*Chrysodomus tabulatus Baird Pl.
*Cryptomya californica Conrad Pl.
Galerus filosus Gabb Pl.
*Siliqua patula Dixon Pl.
*Macoma edulis Nuttall Pl.
*Macoma inquinata Deshayes Pl.
*Modiola recta Conrad Pl.
*Nassa fossata Gould Pl.
*Nassa mendica Gould Pl.
*Olivella biplicata Sowerby Pl.
*Purpura canaliculata Duclos Pl.
*Saxidomus gracilis Gould Pl.
*Solen sicarius Gould Pl.
*Standella californica Conrad Pl.
*Tapes staminea Conrad Pl.

In a small cañon about half way between Mussel Rock and Twelve Mile House, a section of these Merced beds may be observed, at about, probably, the middle of the series, in which trunks of trees are imbedded which project out from the vertical banks into the cañon. With these trees are associated cones, which Professor Greene informs me are those of Pseudotsuga taxifolia (Douglas spruce). The timber of these trees is well preserved, and as erosion exposes the trunks, the people of the neighboring ranch cut them into firewood. In vertical section above this Pliocene kindling

*Still living.

are marine shells, among which the following species were identified for me by Dr. Dall:—

Crepidula prærupta.
Nassa mendica.
Nassa prob. californiana Conr.
Pleurotoma (spec. indet.)
Olivella prob. biplicata.
Cardium (fragment).
Bittium filosum Gld.

Upon such palæontological evidence rests the determination of the Merced series as of Pliocene age. The stratigraphical observations of the writer are in harmony with this determination.

Thickness.—The Merced series, as exposed in this very favorable cliff section, has been subjected by the writer to systematic observations for strike and dip, with the object of obtaining data upon which to base an estimate of its thickness. The observations were taken along the base of the sea-cliff from Mussel Rock to Lake Merced. In deducing the results from the observed strikes and dips it was found convenient to divide the section into a number of separate parts, in each of which the strike and dip are sufficiently constant to give reliable averages. The sum of the thickness of these parts is the total thickness of the series. The results are given below. Should they seem incredible to any doubting geologist, the section is easily accessible from San Francisco, and the writer invites inspection of the section, as one of the most imposing and instructive that he has anywhere met with.

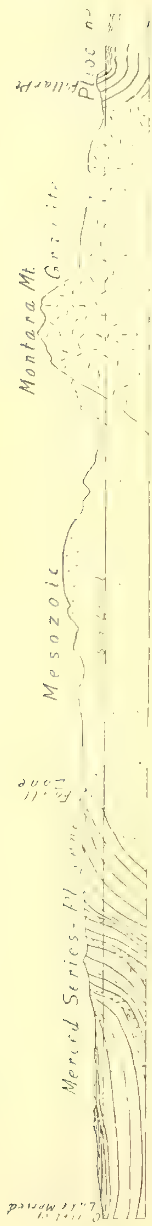

FIGURE 1.—Diagrammatic Section from Lake Merced to Pillar Point. Distance about 17 miles. Vertical Scale twice horizontal.

Measurements for Thickness of Merced Series in Cliff Section, from Mussel Rock to Lake Merced.

Distances on shore, beginning at north side of Mussel Rock.	Range of strike and dip.	Actual thickness of strata crossed by line of section.
2,239 ft.	Strike* 134° to 108°, Dip, 15° to 28°	608 ft.
1,062 "	" 108°, " 28° to 54°	646 "
812 "	" 108° to 114°, " 54° to 72°	696 "
1,614 "	" 113° to 119°, " 59° to 75°	1,302 "
1,500 "	" 118° to 134°, " 75° to 58°	989 "
2,250 "	" 119° to 137°, " 58° to 72°	1,198 "
625 "	" 137° to 140°, " 50° to 18°	187 "
6,250 "	Strike parallel to shore line, *i. e.*, to line of section	0 "
3,646 "	Strike, 150° to 166°, Dip, 39° to 5°	208 "
19,998 ft. Say 2,000 ft.	Total thickness of Merced series exposed in section, 20,000 ft., or 3.78 miles in length	5,834 ft.

*The bearings refer to the true meriidan and read from 0°=N, in the direction in which the hands of a clock move.

At the summit of the volume of strata here measured, there is evidence of scouring of the beds by current action, and the deposition of sandstones upon the beds so scoured in unconformable relation. At this horizon also appear peaty beds. This unconformity, together with the appearance of the peaty beds, is assumed by the writer to mark the close of the Pliocene sedimentation, and the hundred feet or more of tawny sands and sandstones which repose upon these peaty beds in nearly horizontal attitudes, are therfore regarded as of Pleistocene age.

Here, then, we have marine Pliocene sediments laid down to a *thickness of over one mile*, a condition of affairs unparalleled, so far as our records show, on this continent. It is not supposed that the marine Pliocene of the coast has in general a thickness equal to that of the Merced series. It is undoubtedly a local or delta accumulation at the former outlet of the drainage of the country. In this respect we have its modern analogue in the broad, flat embankment accumulating in front of the Golden Gate. In the great Valley of California we have, however, Pliocene and Pleistocene sediments (delta material, probably mostly non-marine) to a depth of at least 2,000 feet. There can be little question as to the propriety of cor-

relating the lower and major portion of the delta which thus fills the Valley of California with the marine delta which constitutes the Merced series, both being due to the same geological causes and processes operating at the same time. The delta gravels exposed on the San Benito to a thickness of at least 1,200 feet are, also, as will be shown in the sequel, of Pliocene age, and are the direct equivalent of the Merced series.

Depression and Uplift.—The character of both the Merced series and of the delta which fills the Valley of California, so far as it is known from the record of wells, indicates that the accumulation could only have proceeded with a concomitant depression of the coast. This depression will not here be further discussed beyond the statement that it is in harmony with other facts, which have been elsewhere noted, indicating that the Pliocene generally on the west coast was a time of epeirogenic depression. It is desired rather to direct attention to the evidence of general and local movement, which has affected this part of the coast in post-Pliocene time.*

The fact of finding fossiliferous Pliocene strata at elevations of over 700 feet is, of course, absolute demonstration of an elevation of the coast to that extent in post-Pliocene time. This itself might, however, be due to the general uplift which has affected the entire coast. This general uplift is but a factor in the total effect of the movements which have been active on the San Francisco Peninsula in post-Pliocene time. The occurrence of a volume of Pliocene strata over one mile thick inclined at high angles (up to 75°) is absolute demonstration of very important differential movements of a local character. The base of this great volume of strata exposed above sea at the same level as the summit of the series, with so small a horizontal interval between summit and base, tells us, in language more forcible than words, the measure of this differential movement. The pre-Pliocene surface, on which flourished the Monterey pine, has, since the inauguration of Pliocene sedimentation,

* The only reference which the writer can find to this subject is a brief note by Mr. Amos Bowman on "Coast Surface and Scenic Geology," Proc. Cal. Acad. Sci., July 1, 1872, which, though somewhat poetic in character, has the merit of recognizing a post-Pliocene uplift of 700 feet on this part of the coast.

been depressed over a mile beneath the waters of the Pacific, buried beneath that thickness of strata, and has since, in the most recent geological epoch, been elevated far above tide. It is this differential movement, of a mile or more, of the country to the southward of Lake Merced which has caused the deformation and tilting of the Merced series.

Discrimination of Orogenic and Epeirogenic Effects.—In the consideration of the diastrophism which has affected the San Francisco peninsula we have, then, two displacements to deal with, the orogenic, or local, and the epeirogenic, or general uplift. Is it possible to discriminate the two effects?—Certain striking facts suggest an answer to this question in the affirmative. The orogenic uplift preceded the epeirogenic, and there was an interval between the movements in which a great denudation was affected. The facts are as follows: The line of demarkation between the Pliocene and the Mesozoic terranes is a nearly straight line coincident with the projection of the axis of the San Andreas Valley to Mussel Rock. This line also separates a country which, in general, has an altitude of less than 700 feet (the Pliocene terrane) from a more elevated tract (the Mesozoic and granite terranes), which culminates in Montara Mountain at 1,940 feet above sea. To the northeast of this line the Pliocene prevails in great volume, as above described. To the southwest the country has now practically no mantle of Pliocene, although such a mantle certainly once existed, since the Pliocene strata structurally arch over it. An occasional pebble is all that remains of the Pliocene strata on the higher ridges and along the shore on the lower slopes. Only insignificant patches of these formations may be found between Mussel Rock and the vicinity of Pillar Point, where the Pliocene again appears in force, and continues down the coast for several miles. Such remnants, with the exception of a single pebble, have not as yet been found above an altitude of 720 feet, although the peninsula, as far south as Pillar Point, has been carefully examined. How is it that the Pliocene to the northeast of the line of demarkation has been preserved so intact, while the country to the southwest, above the altitude of say 700 feet, has been completely denuded of the same formations? —An adequate explanation may be found in the hypothesis that the

differential movement arched the peninsular region in such a way that the portion of it which lies to the southwest of the present line of demarkation was elevated above sea level and subjected to a long, continuous, and vigorous erosion, while the part to the northeast of the line remained below sea level, and was thus protected, being only lifted to its present position by the much more recent epeirogenic uplift of the coast. It is now being removed with astonishing rapidity.

Development of Montara Mountain.—The orogenic event here described, by which the Merced series was lifted into its present position as the limb of a great anticlinal arch, implies unavoidably the post-Pliocene upthrust of the granite mass whose summit is Montara Mountain. This mass resembles in its structure an acutely domed laccolite. The strata of all ages dip away from it quaquaversally. In this respect it closely resembles Mount Diablo, whose structure has been studied by Turner,* with this exception, that the igneous rocks in the core of Diablo are basic. Its upthrust corresponds, also, in age with that of Diablo, as determined by Turner. In neither Montara nor Diablo, however, is the structure laccolitic. The granite in the one case, and the basic igneous rocks (diabase) in the other, were both in place, as the rocks we now know them, beneath the seat of the present mountain masses prior to the upthrust. In both cases the mountains have been formed by a sort of upward telescopic thrust, which *may*, of course, have been due to tangential forces. In neither case was there any apparent development of igneous rock during the movement. The upthrust tilted the strata quaquaversally from the rising central mass. In the case of Montara Mountain the resemblance to the laccolitic structure is the more striking because the central core of the mountain is an extensive granite mass. This mass, however, antedates the oldest sedimentary strata on its flanks, as is well attested by basal conglomerates, composed of bowlders and pebbles of the granite. This type of mountain structure must be carefully discriminated from the true laccolite.

One other point requires to be noticed in connection with the differential movements of the San Francisco Peninsula. The line

* Bull. Geol. Soc. Am., Vol. II, pp. 383–414.

of demarkation between the Pliocene and the Mesozoic rocks, which extends from Mussel Rock southeastward, is in part, also, the trace of a post-Pliocene fault. The great slide on the north side of Mussel Rock is near the land terminus of this fault zone, where it intersects the shore line. Movement on this fault zone is still in progress. A series of depressions or sinks, occupied by ponds, marks its course. Modern fault scarps in the Pliocene terrane are features of the country traversed by it.

Thus we have at our doors, at the University of California, a most wonderful chapter of geological history spread out for our perusal, so that he who runs may read; all the more wonderful because the events recorded are occurrences of but yesterday, and are still in progress. To geologists this brief note on the Merced series is but an announcement of some of the salient facts of a subject which the writer hopes to be able to discuss more fully in a future paper.

THE EVIDENCE FROM THE RIVER VALLEYS.

The conception of the general uplift of the coast from the Golden Gate to San Diego, which is forced upon us by a study of the coastal topography, is fully confirmed by what is known of the topography and geological character of the chief river valleys of the coast. The more important of these are the (1) Santa Clara-San Benito, (2) Salinas, (3) Santa Maria, and (4) Santa Clara of the South. Only the first two of these have been examined by the writer; fortunately, however, we have, also, useful information respecting the other two. The evidence from these four valleys will be briefly considered in the order named.

The Santa Clara-San Benito Valley.—The Santa Clara Valley is the continuation to the southeastward, between the Mount Hamilton and the Santa Cruz Ranges, of the depression which contains the Bay of San Francisco. It in turn passes without essential change of character or of direction into the valley of the San Benito River, which lies between the Mount Hamilton and Gavilan Ranges. The three valleys, thus differently named the Bay of San Francisco, the Santa Clara, and the San Benito, form a single topographic feature. For this combined valley, whose essential

or genetic unity will probably not be questioned, the name which appears at the head of the paragraph is proposed. Its total length from the Golden Gate southwestward may be placed at 150 miles. The breadth of its bottom varies from that of a head-water gorge to about 17 miles at the Bay of San Francisco. It has a remarkably straight course for its entire length. This valley is occupied by a trenched and terraced Pliocene delta. This fact is not so apparent at the middle or Santa Clara portion of the valley as it is at its lower and upper portions. The lower portion is partially occupied by the Merced series, which has already been described. The upper portion, from the Pajaro Cañon southeastward, reveals the delta in a great volume of appromimately horizontal gravels. The Pliocene age* is established by their unconformable relation to the upturned Miocene of Pajaro Cañon, and by the fact that they contain pebbles of the white, siliceous shale which characterizes the Miocene of the coast. These gravels are exposed on the San Benito, the Tres Pinos, and Los Meritos in a series of very remarkable cliffs, often over 1,000 feet high, which are being developed by a vigorous sort of sculpture which yields the effects of a "bad land" topography (see Plate 9). The trenching and terracing action of the streams, as they have by stages dissected the delta during the progress of the uplift, has left remnants of it in the form of isolated hills and plateaux in the middle of the valley. One of the highest of these lies just above the confluence of the Tres Pinos and the San Benito between the two streams. This plateau shows magnificent cliff sections, particularly on the San Benito side, and the character of the ridge as a series of well-bedded gravels from top to bottom is evident to the most casual glance. The bedding is either horizontal or is tilted to the eastward at angles up to perhaps 15°. The altitude of the summit of the gravel plateau was made the subject of careful measurement. By the use of the mercurial barometer the summit was found to be 929 feet above Tres Pinos

* Whitney recognized these gravels as Pliocene, but without, as Dall points out, adducing evidence for this conclusion. In his "Geology of California" he gives them but a passing reference, without expressing an opinion as to their age. In his later work, "The Auriferous Gravels," without having further examined the field, he simply states that they are of Pliocene age.

PLICCENE DELTA OF SANTA CLARA-SAN BENITO VALLEY, ABOVE TRES PINOS.

station. The latter is given in the railway levels at 514 feet above sea level. The summit of the plateau is thus 1,443 feet above sea level. It is clear, from the character of the ground, that the summit of the plateau is not the original summit of the delta formation; much has been removed by erosion. Further up the valley, also, these same gravels are known to the writer to be several hundred feet higher than on the plateau near Tres Pinos. The summit and slopes of the plateau are distinctly terraced at various levels.

In these facts we have all the evidence that could be desired for the conclusive demonstration of (1) the depression of the coast in Pliocene time during the accumulation of the gravels, (2) the great volume of the Pliocene strata, certainly not less than 1,200 feet, (3) the correlation of the San Benito gravels with the Merced series at the lower end of the same valley, (4) the uplift of the valley with its load of gravel, in post-Pliocene time, to an extent not less than the measure of the altitude of the plateau near Tres Pinos.

Two other facts of interest remain to be mentioned: 1. At the confluence of the Los Meritos and Tres Pinos Creeks, about eight miles above Tres Pinos station, these same Pliocene gravel beds, which, like the "auriferous gravels" of the Sierra, are often firmly cemented, are faulted and thrown into vertical attitudes, clearly showing that the region has been subjected to the action of important orogenic forces in post-Pliocene time. 2. In passing through the middle or Santa Clara portion of the valley, the valley bottom *appears* to be a level plain. From its relation to the Bay of San Francisco, and its flat, unterraced surface, one is impressed with the belief that this portion of the valley owes its character to its having been very recently at base-level, a continuation, in fact, of the mud flats of the bay. Assuming this base level origin for the flat, unterraced *surface* of the Santa Clara plain, we are confronted with the remarkable fact, that the plain is not only *not* what it appears to be, viz., level, but that it has not a uniform slope. The railway profile which passes through the center of the plain shows a steady upward grade from San Jose, at 86 feet, to Madrone, at 342 feet, a distance of 18 miles, or 14 feet to the mile. This is the highest part of the plain, and probably its most level part. Beyond Madrone the grade descends, till at Sargents, 18 miles to the south-

ward, the track has an altitude of 135 feet, being a grade of 11.5 feet to the mile; thus the longitudinal profile of the plain is a low arch. If the surface of the plain once had a uniform slope, as our assumption implies, this arch must be due to local differential movement or deformation of very recent date.

The Salinas Valley.—This valley opens broadly on the Bay of Monterey, and extends up between the Gavilan and Santa Lucia Ranges as far as Santa Margarita, a distance from the mouth of the Salinas of about 120 miles. Next to the Santa Clara-San Benito Valley, it is the largest and most important of the many beautiful valleys of the Coast Ranges. Like that valley, its course is remarkably straight, and has a northwest and southeast trend, being parallel to the coast line. This valley also is occupied by a trenched and terraced Pliocene delta, composed of generally horizontally stratified beds of gravel, sand, and clay (the latter in the lower part of the valley), resting uncomformably upon the upturned Miocene and older strata, and being largely composed of the débris of white, siliceous shale like that of the Monterey series. The structure of the delta is well exposed in the many railway cuttings and natural scarps of the upper portions of the valley. The delta material is evidently very thick, but its volume cannot be estimated as closely as on the San Benito. Stream terraces are abundantly represented, and register clearly the different stages of the uplift. They have been observed by the writer on the sides of the valley at numerous localities from its lower stretches up to a little above Paso Robles.* The present summit of these delta beds has an observed altitude, a little below Santa Margarita, of about 1,100 feet, and they probably have a much higher elevation on the hills back of the railway, which was made the line of a series of hurried observations. Thus again we have in the topography and geological character of the valley abundant evidence of its recent uplift; and, from the relation of the valley to the Bay of Monterey, there can be no question as to the correctness of correlating its stream terraces with the wave-cut terraces of Santa Cruz. It also seems clear that the valley in which

* Three terraces were recognized by Trask and by Antisell in the lower part of the Salinas Valley. See Jour. Senate Calif., 5th sess., 1854, append. Doc. No. 9, p. 48. and Pacific Ry. Reports, Vol. VII, Part II, pp. 38, 39.

the delta lies is a valley of erosion (probably along a fault line), antedating in its origin the Pliocene deposits, and following the post-Miocene uplift.

The Santa Maria Valley.—This valley has not been visited by the writer, but some very explicit and suggestive information concerning it has been placed on record by Antisell.* His statements are here quoted: "The Santa Maria or Cuyama Valley differs from any other observed in not having a true outlet. On the south it is shut up by the San Emilio mountain region; on the east, by the low porphyritic feldspar range running into that mountain also; on the north it is occluded by the cross ranges given off from the Santa Lucia, and by this range on its west, throughout the whole length; it is completely shut in, except at the point where the river cañons through the narrow gorges of the Santa Lucia. This is a channel which the river itself has partly cut for itself, and can scarcely be called a natural outlet of a plain. The slope of the base of the plain is to the north by west, and would naturally pour its waters into the small valleys of San Jose and Santa Margarita were it not prevented by the serpentine ridges crossing it at the head of these localities. The observer, first casting his eye over the extended plain, widening towards the south by the recession of the mountain ranges, would at once set it down as the basin of a great arm of the sea, which ran up towards the north, and that the natural debouche was towards the southeast, or opening into Tulare plain. This may have been the case once; but at such time Tulare plain itself was not so elevated or cut off from communication with the desert east as at present. The elevation of Tulare and Santa Maria were coeval. The sandstones and gypseous beds found northwest of the Cañada Uvas may be traced round the side of the porphyry domes into Cuyama Valley as a continuous series, elevated by the same local action; and as the Estero plain lies between Tulare and Santa Maria Valleys, upon the crests or in a trough between the porphyry ranges, the continuation of the San Jose Range, which also stretches under Panza and Cariso, that plain (Estro) belongs to the same age, and the San Jose Range, by its elevation, separated for the first time the previously connected plains of Cuyama and Tulare Valley.

*Pacific Railway Reports, Vol. VII, 1857, Part II, pp. 55–57.

Whichever may have been the outlet—which at present is closed up—it is, perhaps, difficult to decide now; but the valley everywhere, especially at the lower end (north), presents the usual marks of running water in the terraces found on its mountain sides, and on such a large scale as to induce the examiner to look upon the whole plain as once an extensive lake, the level of whose waters were then 200 feet above the present level of the plain below. . . . The present river flows about four to six feet below its bank; the bottom of the river forms an alluvial flat about a mile in breadth; on each side of this a higher plain, the more ancient bottom, extending for a mile on each side, and about twelve feet higher than the true bottom. This ancient bottom reaches to the foot of the mountain ranges. Thirty feet high on the San Jose Mountains a terrace is found, which may be traced for several miles north and south; the line of the terrace is not horizontal, but apparently falls to the southeast; this may, however, be only apparent, as the level of the plain slopes in the opposite direction. Opposite to this, near the camp at Quadre Domingo, the terrace on the sandstone of the Santa Lucia is about the same height, and is covered with pebbles of red and green conglomerate, quartz, and porphyry. That on the San Jose is white clay and sand rock in angular fragments, with pebbles of the opalescent quartz found underlying the ostrea bed of Santa Margarita. Above the terrace line is that one first described. The order of all these would lie thus":—

—	Total elevation above sea, in feet.
Terrace 100 to 150 feet high on mountain	1,690
Terrace 30 feet high on mountain	1,542
Terrace 12 feet high, old river bottom	1,512
Terrace, present river bottom, river 4 feet below	1,500

The terraces thus described by Antisell afford us no direct means of estimating the uplift which they record. It is a bare possibility, even, that they may be due simply to the drainage of a lake by the trenching of a barrier. But, taken with the other facts as to the recent elevation of the coast, it seems probable that they are to be ascribed to the same general cause as in the other cases described. If, as Antisell maintains, the ancient outlet has been choked, and a

new one is being cut, the choking was doubtless due to accumulation of delta material during the Pliocene depression, and the facts are in harmony with our notions of a post-Pliocene uplift, although we cannot from the information given make deductions as to its measure.

The Santa Clara Valley of the South.—This valley extends from Soledad Pass in the mountains overlooking the Mohave Desert, with a trend a little south of west, to the coast below San Buenaventura, where it opens funnel-like upon the Santa Barbara Channel. The valley affords a pass for the railway to the coast. From the railway junction at Newhall, according to information given to the writer by a friend, who, as a traveler, is familiar with the country, the slopes of the valley are terraced up to elevations of probably not less than 150 feet above the railway. The railway track at Newhall has an elevation of 1,265 feet,* from which it appears that the terraces have an altitude of 1,415 feet above sea. The information is defective, inasmuch as the nature of the terraces has not been critically determined; but, taken with other more definite information set forth in this paper, there is little doubt but that they are significant of uplift of the coast.

CONCLUSIONS.

The facts adduced in the present paper establish a recent uplift of the continental margin, from the Golden Gate to San Diego, of from 800 to 1,500 feet. The geographical extent of the uplift is not measured by the range of the observations here recorded. There is evidence that the uplift extends far to the south and far to the north of the strip of coast subjected to inspection. The uplift is clearly epeirogenic in its character.†

This event is comparable to the well-known post-Pliocene diastrophism of the Sierra Nevada. Accepting Whitney's determination of

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*Gannett, Bull. U. S. G. S., No. 76.

† This statement does not imply that all parts of the coast were elevated at precisely the same time, but simply that the effect, up to date, of the elevatory process is an uplift of continental extent. The process *may* have been fitful, active now in one locality, now in another; the movement may have operated as a slow wave, or it may have had a single focus of direct uplift; it may yet be active.

the "auriferous gravels" as of Pliocene age, the tilting of the Sierra Nevada peneplane was also a post-Pliocene event. The Valley of California affords evidence of but very moderate uplift, as compared with that of the Sierra on the one hand and the coast on the other. It appears, therefore, that whatever may have been the origin of the valley, whether the result of erosion or of structural depression, it is, in the recent phases of its development, a synclinal trough. The tendency of the coastal uplift to make the valley a closed basin has been counteracted by the vigorous trenching of the mountains effected by the Sacramento River at the Straits of Carquinez. It is not yet known whether this trenching action has *always* been able to keep pace with the rate of uplift so as to maintain the drainage of the valley at base-level. It is also improbable that this outlet antedates the Montara and Diablo upthrusts. In so far as the epeirogenic uplift has accentuated the character of the Valley of California, it has incidentally given us an *orogenic* result.

As a consequence of the general uplift of the coast, the physiography of the country has been radically changed in the most recent geological times. During the Pliocene depression many of the valleys, which had been developed in the post-Miocene interval of high altitudes, were filled to the brim with delta deposits. *Pari passu* with this filling process, the hills were being worn down to near base level. The result at the close of the Pliocene was an approximation to a peneplane topography—a peneplane partly of delta construction and partly of mountain truncation. Remnants of this peneplane are apparent in parts of the southern coast ranges in the plateau-like summits of the lower ranges, although it is possible that some of this peneplane effect may be ascribed to the much earlier Miocene depression. The two truncations, Pliocene and Miocene, will, in the opinion of the writer, be readily discriminated in detailed field work. At best, however, the Pliocene truncation resulted in but an approximation to a peneplane, or series of local peneplanes. Numerous peaks and ridges rose above the general level. Numerous islands, large and small, fringed the coast of California. There were numerous submerged valleys, so that the coast was well supplied with harbors. In a word, the coast of California, at the close of the Pliocene, had the aspect of an archipelago. The

archipelagic condition endured into the early Pleistocene, and from this condition it has been gradually recovering up to the present day. The Channel Islands may be regarded as the remnants of this late Pliocene and early Pleistocene condition. The uplift has robbed the coast of its ancient harbors, and the only notable one of the present day exists by grace of special and local, but very vigorous, orogenic movements on the Peninsula of San Francisco. With this radical transformation in the physiography of the coast, there have doubtless been very important changes in the climate, and in this fact is to be found, probably, the explanation of certain remarkable and anomalous features in the distribution of the plants of the coast. A map of the shore at the beginning of the Pliocene would resemble the one of to-day. A map at the beginning of the Pleistocene would resemble rather that of the present Alaskan shore-line.

In the continuous chain of geological events from the inauguration of the Pliocene to the present time, it is not an easy matter to delimit the Pliocene and Pleistocene epochs so that they shall correspond to the same divisions of the geological scale in the eastern part of the continent. The difficulty is the greater if we depend entirely upon palæontological data; and, probably, a satisfactory definition of the Pleistocene of the west coast as distinct from the Pliocene, will never be formulated upon a purely palæontological basis. The reason for this is that there has been no distinct break in the continuity of marine conditions throughout the epochs, only a gradual transition of conditions. In this gradual transition there was, however, a reversal of the epeirogenic movement of the coast from a process of depression to a process of uplift. This turning point of the diastrophic pendulum, the initiation of the diastole of the epeirogenic pulsation, is believed to correspond well with the beginning of the Pleistocene. The two epochs thus delimited have no interval of erosion between them, and there will be found no marked break, except locally, in the sequence of marine life. On the other hand, the Pliocene is separated from the Miocene by an important interval of erosion. It follows that the subdivision of the Tertiary, or Cainozoic into Eocene and Neocene is not suited to the west coast. The Miocene is distinct. The Pliocene merges into the Pleistocene, and the marine strata of the two epochs must, to a large extent, be mapped together.

While epeirogenic processes have thus been active, orogenic forces have not been at rest. Important local differential displacements of the crust have occurred. The instances noted are probably representative of other similar orogenic displacements not yet known.

In the case of Santa Catalina Island these are manifest in a depression of the island relatively to the land masses on either side. This depression may have been subsequent to the major portion of the epeirogenic movement, or may have been concomitant with it.

In the more notable case of the San Francisco Peninsula orogenic action is very apparent in the upthrust of Montara Mountain, and the consequent deformation of the Merced series (Pliocene). This upthrust, unlike the Santa Catalina depression, seems to have preceded the general uplift, and the two events may be discriminated. The effect of the upthrust has been to produce a mountain with a granite core and flanking strata dipping quaquaversally from it. There are two types of mountains which have this structure, viz., the *laccolitic* and the *batholitic.* Montara Mountain is a type of structure distinct from either of these, since the granite is not intrusive in the flanking strata, but represents the basement upon which they were deposited. This upthrust in a locality where the Pliocene strata are excessively thick, suggests interesting speculations as to the much discussed relations of accumulation to diastrophic movements. For the accumulation of the mile of strata represented by the Merced series, the coast must have been locally depressed. A limit seems to have been reached and upthrust to have at once set in. The local character of the subsidence, the excessive accumulation, and the strongly pronounced upthrust, are peculiarly interesting, and invite the attention of students of diastrophism. The post-Pliocene upthrust of Montara Mountain is in harmony with Turner's conclusions as to the post-Pliocene origin of Mount Diablo, and the two events are probably to be correlated. Were similar conditions of excessive accumulation associated with the birth of Diablo? Can overloading by any possibility be assigned as the cause of the relative or absolute depression of Santa Catalina?

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THE LHERZOLITE-SERPENTINE AND ASSOCIATED ROCKS OF THE POTRERO, SAN FRANCISCO.

BY

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CONTENTS.

INTRODUCTION.

THE portion of the city of San Francisco known as the Potrero is a triangular area of about one square mile, lying between San Francisco Bay and Mission Valley. It is occupied by a ridge of hills with northwest and southeast trend, which attain an elevation of 360 feet near the center of the area, and on the land side gradually diminish in height and pass into the floor of the valley. On the bay side the hills in places approach the shore in high bluffs, but

for the most part slope gently down to the shore level. Although but few houses occupy this area, streets have been run through it in all parts, and numerous cuttings expose large sections of the underlying rocks. The surface of the Potrero is almost wholly occupied by a mass of serpentine, a portion of the more or less irregular belt of that rock which traverses the peninsula in a northwest and southeast direction from Hunter's Point to the Presidio. Associated with the serpentine are shales and sandstones of the San Francisco sandstone formation, thinly bedded jaspers (phthanites of Becker), and certain masses of intrusive rock of very peculiar occurrence.

The unusual opportunities afforded in this area for the study of the structure and for obtaining fresh specimens of the rocks, led to the hope that evidence might here be found bearing on the origin of the serpentine; and with that object particularly in view, the investigations, the results of which are here set forth, were made.

The details of the petrography of the serpentine which will be found below, presenting, as they do, no new fact in the history of the formation of that mineral, may be considered unnecessarily minute in view of the knowledge of that process at the command of petrographical students. But as the igneous origin of the serpentine of the Coast Ranges has been denied, and as other hypotheses of its formation have been advanced,* it was thought proper to give in full the evidence which has been collected of its

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Becker, G. F., "Quicksilver Deposits of the Pacific Coast." "Monograph XIII," U. S. G. S., pp. 120–128.

Note.—Since writing the above there has come to the writer's notice a paragraph by Dr. Becker which it is but justice to him to quote. In "Extract from Mineral Resources of the United States, 1892," Quicksilver Ore Deposits, p. 9, Dr. Becker says: "After the publication of 'Monograph XIII,' Mr. H. W. Turner, acting as my assistant, proved to his own and my satisfaction that the serpentines of Mt. Diablo are mainly or wholly due to the decomposition of peridotite and other basic eruptives not previously recognized in the Coast Ranges. This investigation convinced me that portions of the serpentines classed as metamorphic in 'Monograph XIII,' in the absence of known evidence to the contrary, are also of eruptive origin. This additional information does not derogate from the importance or the interest of the occurrence of metamorphic serpentines in the Coast Ranges."

derivation from an eruptive rock in this area, and thus add one more to the short list of such occurrences as yet described on this coast.*

THE SERPENTINE.

Outcrops.—The serpentine appears in rounded hills, which are bare and strewn with rock fragments of local derivation, or are covered with a scant soil, probably largely of æolian origin, in which similar fragments of the underlying rock are imbedded. These fragments are mostly small and rounded by weathering. In places the outcrops protrude above the soil to a height of five or six feet, presenting irregular pitted surfaces fashioned by weathering into most fantastic shapes. Where the surface is free from rocks there is generally a poor growth of grass, plainly showing the thinness and poor quality of the soil beneath, which, except in alluvial depressions, is never more than a few inches in depth.

Petrographical Character.—The serpentine assumes at least two well-marked facies, which for the purpose of description may be designated the "slickensided facies" and the "massive facies."

The slickensided facies, which composes the greater part of the serpentine mass in question, is chiefly characterized by the abundant evidence of internal movement which it displays. This evidence is of two kinds: 1. The presence of surfaces both plane and curved, intersecting the rock mass in all directions, along which relative motion of the rock particles has taken place. 2. The faulting of veins of secondary minerals in the rock and the bending of crystals imbedded in its mass.

The presence of these surfaces of movement gives rise to the appearance suggested by the name given to this facies of the serpentine, each surface being in reality a slickensided surface. So numerous are these surfaces that no fragment of the rock, however small, can be obtained which is not bounded by them. They are sometimes parallel or concentric, and so close as to give the rock a leafy or scaly structure, which causes it to rapidly crumble away when exposed to the atmosphere. The surfaces are smooth and at

*M. E. Wadsworth, "Lithological Studies," Vol. XI, Part I. Mem. Mus. Comp. Zoölogy, Harvard College, 1884, pp. 129–132, 158. Turner, H. W., "Geology of Mt. Diablo," Bull. Geol. Soc. Amer., Vol. 2, 1891, pp. 388–391. Merrill, G. P., footnote to above, p. 389.

times polished, and have a greasy feel, like talc. The rock varies in color from a dirty white to a peculiar bluish-green tint. Traversing the rock in places are veins of chrysotile, the silky fibers at right angles to the walls, and bands of marmolite of various shades of green and blue. These sometimes alternate in parallel layers, and more rarely change from one to the other. Minute faults may be seen in these veins, giving evidence of movement of the rock after their formation. Threads of magnetite penetrate the serpentine, and the slickensides are in places incrusted with small octahedral crystals of that mineral. In one locality a vein of earthy magnesite occurs; at its point of greatest thickness it is about six inches across, but divides into smaller veins and then thins out. It cuts the serpentine almost horizontally, extending along the face of a street cutting for a length of about seventy-five feet. Chalcedony occurs in a few places as a coating on the serpentine or in veinlets.

On large exposed surfaces of this facies of the serpentine there frequently appear spheroidal masses, sometimes very numerous, of diameters ranging from six inches to three or more feet, separated from one another by bands of the crushed and slickensided material. These masses give the rock almost the effect of a boulder conglomerate. The interstitial serpentine is crushed and drawn out around the spheroids, having the appearance of a plastic cement moulded to them. On examination, these spheroidal masses are found to be portions of the original rock mass, which have escaped the shearing and complete decomposition to which the rest of the rock has been subjected, their rounded forms being due to the wearing away of the angular portions by repeated movements of the surrounding rock in every direction. The character of the rock composing these spheroids will be described in detail under the heading of the "massive facies."

In certain limited areas the serpentine has escaped the general crushing action. In such places it appears as a typical massive serpentine, dark green in color, translucent on thin edges, with subresinous luster and splintery to conchoidal fracture. In some specimens no other mineral is present except small crystals of chromite and magnetite. More commonly there are scattered crystals of enstatite imbedded in the massive serpentine, noticeable

on account of their brilliant cleavage faces. Limonite is also present in varying amount, sometimes invading the whole mass of the rock, rendering it gray or brown in color, and quite opaque, with a decidedly porcellanous aspect. Under the microscope all these varieties of the serpentine have a similar aspect, and are also identical with the serpentinous groundmass of the massive facies next to be described. Their characters will, therefore, be described under that heading.

The massive facies is most characteristically exhibited in the spheroidal masses, of which mention has been made, but it is not confined to them, several varieties of it being abundantly developed in other forms. The freshest phase of the rock which occurs in those spheroids least affected by shearing is dense and massive, dark green in color, tough and of uneven fracture. Its specific gravity, determined on several fragments, is 2.66.

Macroscopically it appears to be chiefly composed of serpentine, homogeneous and translucent in thin splinters, imbedded in which are numerous crystals of pyroxene, with brilliant cleavage faces, and grains of magnetite.

Under the microscope, serpentine is seen to be the predominating mineral. Imbedded in it are numerous pyroxene crystals of varying dimensions, less abundant grains of olivine, and grains of chromite and magnetite.

The serpentine is colorless in most sections, having a slight tinge of green. Its structure is not apparent in ordinary light, but with crossed nicols it is seen to be a colorless felted aggregate, too fine to be studied as individuals with the microscope. The serpentine aggregate exhibits weak double refraction, the interference colors never surpassing a pale yellow, and being more commonly of gray tints. Between crossed nicols it retains nearly the same tint throughout a complete revolution of the stage, owing to compensatory extinction of the irregularly oriented serpentine fibers. While a large proportion of the serpentine is thus lacking in any definite arrangement of its component fibers, in places narrow bands, in which the fibers are approximately parallel, are seen to inclose areas of confused orientation. By their mode of arrangement these bands give rise to the well-known types of structure,

the *grating* structure and the *mesh* structure. The grating structure is characteristic of areas of serpentine derived from enstatite and diallage; in it the bands of parallel fibers are in position corresponding to the direction of the dominant cleavage in the original mineral. The fibers are at right angles to the lengths of the bands. The mesh structure is found in areas of serpentine derived from olivine. In this structure the bands intersect somewhat irregularly, but generally in rectangular positions, surrounding eye-like areas of felted serpentine. The bands are frequently marked by a concentration of limonite and magnetite along their course in both types of structure. Experiments made on several thin sections of serpentine proved that it was readily gelatinized by both hydrochloric and sulphuric acid.

The pyroxene is of two kinds, an orthorhombic variety with the characters of enstatite, and a monoclinic pyroxene, determined as diallage. The enstatite, which is by far the more abundant of the two, occurs in large individuals, which are very noticeable in hand specimens of the rock, the brilliant cleavage faces causing them to stand out prominently from the dull green of the surrounding serpentine. Though apparently porphyritic in character, these individuals have in no case definite crystal boundaries, but are remnants of an originally coarse allotriomorphic-granular rock which have escaped the serpentinization affecting most of the mass. In thin section it is colorless and presents one dominant cleavage parallel to the brachypinacoid. The prismatic cleavage may be recognized in basal sections, but is feebly developed. The interference colors are low, varying from pale green to yellowish gray, in this respect presenting a marked contrast to the diallage found in the same slide. Cleavage fragments exhibit parallel extinction, and plates parallel to the pinacoidal cleavage show no optical figure —features which prove its orthorhombic character. Many of the enstatite crystals exhibit the effect of pressure or shearing force in the bent and twisted condition of their cleavage laminæ, resulting in an undulatory extinction between crossed nicols. The source of this stress probably lies in the increase in bulk of the rock resulting from the hydration and serpentinization of the minerals composing it.

The process of serpentinization, before referred to, may be observed in all stages of development, both as to individual crystals of enstatite, and as to the mass of the rock. In the enstatite the change begins along the cleavage planes, gradually extending in all directions until the whole mass of the crystal is involved. The structure of the enstatite is so well retained, however, that frequently the change can only be detected by use of polarized light, which reveals the more or less complete substitution of the serpentine aggregate for the original mineral. The change is sometimes, but not always, accompanied by the deposition of hydrous iron oxide along the cleavage cracks, the result of which is to emphasize the original structure of the enstatite, as seen in the grating of the serpentine before mentioned.

Diallage is present in quite a subordinate amount in the slides of this rock which were studied. As, however, the diallage changes to a serpentine indistinguishable from that derived from enstatite, and as a large proportion of this rock has undergone serpentinization, it is impossible to ascertain what was the ratio of the two pyroxenes in the original rock. Diallage occurs in the irregularly bounded grains of varying size. It is colorless, and may be recognized even in ordinary light, by the perfection of the orthopinacoidal cleavage. More characteristic features are the appearance of high interference colors between crossed nicols, and the rough surface seen in convergent light. The extinction is inclined, the maximum angle on the trace of the orthopinacoidal cleavage being 38°. Besides the orthopinacoidal cleavage, there is well-marked prismatic cleavage, seen on basal sections. No case of intergrowth between diallage and enstatite was observed, though the two minerals are frequently developed side by side. The diallage exhibits the same pressure effects as does the enstatite, and its decomposition into serpentine was observed in various stages of completeness and offers no points of difference from that of the orthorhombic pyroxene.

Olivine is present in only a portion of the slides which were prepared from this rock, and where present is in small amount. The ease with which olivine is changed to serpentine is, however, well known, and it may well be assumed that it would be the first constituent of the rock to undergo decomposition. As much of

this rock has been serpentinized, it is easily possible that olivine may have been originally an abundant constituent, but it is now almost wholly removed by differential decomposition.

The olivine occurs only in very small grains or fragments imbedded in serpentine. These fragments usually have a common orientation over considerable areas, showing the olivine to have originally formed individuals of large dimensions. It is colorless and has the rough shagreened surface characteristic of olivine, so that it stands out strongly from the surrounding serpentine. It exhibits no trace of cleavage, and as the boundaries of the grains are wholly irregular, no observations for extinction were obtained. The interference colors are very brilliant. Some difficulty was found in distinguishing olivine from certain sections of diallage, but the following characteristics seem to clearly separate them. As the olivine exhibits no cleavage, sections without cleavage may of course be found which show no interference figure in convergent polarized light. But sections of diallage parallel to the orthopinacoid, which, as the prismatic cleavage is frequently not apparent, would exhibit no cleavage, are at right angles to the plane of the optic axes, and show the emergence of an optic axis. As this is the only section of diallage in which cleavage is not visible, it may thus be distinguished from olivine. The alteration of olivine to serpentine takes place in the manner described by so many authors. The meshes of the resultant serpentine frequently contain at their centers residual grains of olivine, and magnetite is abundant in the cracks, as well as limonite.

Chromite occurs in scattered, irregular grains imbedded in the serpentine, but not, so far as observed, included in the original constitutents of the rock. It exhibits the characteristic high relief and dark brown color of chromite, and gives a strong reaction for chromium in a borax bead. Magnetite is found in irregular grains and in octahedral crystals, mostly occupying veins and cracks in the serpentine, but also occurring as inclusions in the original minerals of the rock. No feldspar nor any mineral or aggregate which could be referred to feldspar for its origin, could be discovered in any phase of the rock.

The phase of the massive rock above described is restricted to

very small masses, chiefly the spheroids included in the serpentine. There is, however, a much more abundant form of the rock which serves to connect more closely the rock of the spheroids with the serpentine. In it serpentinization has proceeded so far as to have practically invaded the whole mass, a few scattered grains of enstatite alone remaining of the original constituents. These enstatite crystals retain their pristine freshness, and the serpentine has not been subjected to the crushing and shearing evidenced in the slickensided facies. Veins of chrysotile and marmolite traverse it in places, and in many respects it shows its relation on the one hand to the typical serpentine of the area, and on the other to the rock of the spheroids.

The evidence above presented proves that the serpentine is derived from a crystalline rock whose original constituents were olivine, enstatite, diallage, chromite, and magnetite. It thus has the composition of a lherzolite, and is accordingly so designated.

No chemical investigation of this group of rocks was undertaken by the writer. But the peridotite described by Mr. Turner,* from Mt. Diablo, presents so many points of similarity to the Potrero lherzolite that its analysis by Dr. Melville is quoted. Dr. Newberry† has also described the serpentine of the Presidio, San Francisco, which is geologically continuous with that of the Potrero, and of similar nature. He gives an analysis by Dr. J. D. Easter of a specimen which appears to be similar to the serpentine described in this paper, and this analysis is therefore appended:—

	I.	II.
SiO_2	53.25	39.60
Cr_2O_3	.54	.20
Al_2O_3	2.80	1.94
Fe_2O_3	.69	....
FeO	5.93	8.45
MnO	.09	
CaO	16.22	....
MgO	19.91	36.90
Na_2O	.19	....
H_2O	.29	12.91
	99.98	100.00

* Loc. cit., p. 389 and p. 406, analysis 242.

† Pacific R. R. Repts., Vol. VI, Pt. II, p. 11, 1855.

I. Pyroxenite from Mt. Diablo; analyst, Dr. Melville.

II. Serpentine from Presidio, San Francisco; analyst, Dr. Easter.

The analyses thus shown are of rocks of basic and ultra-basic composition, and it may fairly be assumed that they represent approximately certain phases of the Potrero rocks. While no great weight can be attached to the evidence thus obtained, still, such as it is, it corroborates fully the conclusions previously reached from the study of the structural and mineralogical characters of the serpentine and lherzolite of the Potrero.

Relations of the Serpentine to the San Francisco Sandstone.—The evidence obtained in this area bearing on the relation of the serpentine to the sandstone terrane is not wholly conclusive, although the rocks may be observed in direct contact at several points. At the corner of Solano and Connecticut streets the serpentine may be seen resting on a mass of shaly sandstone, the plane of contact dipping to the north at an angle of about 30°. Blocks of sandstone appear to be included in the serpentine near the contact, but the rock is so sheared up and decomposed that this is doubtful. A similar contact is exposed at the corner of Tennessee and Napa streets, the sandstone again being beneath the serpentine. No evidence of contact metamorphism in the sandstone is visible in either case. On the top of the hill at the intersection of Iowa and Butte streets is a small body of bedded jaspers associated with sandstone resting upon serpentine. The jaspers are violently contorted, but appear to dip towards a mass of serpentine lying at about the same level. In the large quarry on Potrero avenue, at the extreme northern point, is a block of sandstone about three feet in diameter, apparently entirely surrounded by serpentine. At the opposite side of the quarry shaly beds may be seen dipping towards a mass of serpentine which crops a few feet away. Two hypotheses may be made as to the relations of these two formations: (1) That the serpentine is the older terrane, the sandstone having been deposited upon it and subsequently tilted and faulted. (2) That the serpentine is younger than the sandstone and intrusive into it. Reviewing the above facts in the light of these hypotheses, it will be seen that several of the observed relations, notably the masses of sandstone included in the serpentine, cannot be explained by the first one.

The second hypothesis, however, offers a satisfactory explanation of all the facts observed, and is probably the correct one. The fact that other masses of serpentine have been observed by the writer in the vicinity, where the evidence of its intrusion into the San Francisco sandstone admits of no reasonable doubt, strongly corroborates this conclusion. The serpentine of the Potrero has been described by Blake * and Newberry,† both of whom considered it eruptive into the San Francisco sandstone.

Other Occurrences of Serpentine.—Although serpentine is a very abundant rock in the Coast Ranges, there have been, so far as known to the writer, but three descriptions of Coast Range localities published wherein a relation has been traced between serpentine and an eruptive rock. Reference to these descriptions has already been made on page 163 above. In the case of the lherzolite-serpentine described and figured by Mr. Wadsworth,‡ from Colusa County, the evidence seems particularly clear and irrefutable. In view of this fact it seems certain that Dr. Becker must have been unaware of this description when he wrote the sweeping statements contained in "Monograph XIII," as to the absence in the Coast Ranges of serpentine of igneous origin. Mr. Turner's description§ of the Mt. Diablo occurrence corresponds closely to that detailed in this paper, the original rock in both localities being determined as lherzolite. The specimen referred to by Mr. Merrill,‖ from San Francisco, is doubtless from an area of serpentine geologically continuous with that of the Potrero, and the slight difference of mineralogical composition which places this rock with the saxonites indicates merely a local variation, and not an essential difference of the two rocks.

THE INTRUSIVE ROCK.

Occurrence.—Along the western side of the serpentine area is found a belt of isolated outcrops of a dark-colored, crystalline rock, extending parallel to the ridge for a mile, and nowhere more than

* Pacific Railroad Reports, Vol. V, Pt. II, p. 157, 1853.

†*Ibid.*, Vol. VI, Pt. II, p. 10, 1855.

‡ Loc. cit., p. 129.

§ Loc. cit., p. 389.

‖ Loc. cit., p. 390.

three hundred yards in width. The linear arrangement of these outcrops as they appear on the map was strongly suggestive of a dyke or sill, and the petrographical character of the rock, which proved to be an altered hypersthene diabase, made its intrusive origin seem certain. The outcrops, however, were found to be in every case of very limited extent, never more than one hundred feet in greatest dimension, and each completely surrounded by serpentine. The explanation of this rather contradictory evidence was found in a quarry section on Potrero avenue. On the face of the high bank there exposed may be seen a series of slightly inclined, lens-shaped masses of the intrusive rock, each surrounded by serpentine, and separated from the neighboring masses by both horizontal and vertical intervals of varying amount. One of these lenses, which was in perfect contact with more or less slickensided serpentine throughout its circumference, measured twenty-five feet in length and five feet in greatest thickness. The rock showed no evidence of crushing or shearing, but the lens was rounded off and the serpentine moulded to it very much as in the case of the spheroids of lherzolite before described. It is thus evident that the intrusive rock once existed as one or more continuous masses of the form of dykes or sills, which were broken up into the present detached masses by movements of the serpentine. This view of the nature of these masses is confirmed by the fact that the texture of the rock varies with the distance from the contact of the serpentine. In several places where the full width of the dyke was exposed, a definite increase in the coarseness of grain of the rock could be observed as the center of the mass was approached. Whether this well-recognized feature of dyke structure is accompanied by variations in chemical character has not yet been ascertained.

Petrographical Character.—The intrusive rock is normally a massive rock, dark gray to whitish gray in color, presenting in all cases a distinctively crystalline aspect; it is hard and brittle and rings when struck with the hammer. In places a tendency towards a schistose structure is observed, plainly a result of the shearing forces which have been shown to have affected the rock; but this structure is a very local feature. In hand specimens the recognizable minerals are feldspar, generally milky and opaque, horn-

blende in bladed crystals, and grains of pyroxene. Although in the field this rock appears to be fairly uniform, when studied with the microscope it is seen to vary considerably, exhibiting a gradation of forms best described under two types. The first type, which is the most abundant one, appears in thin sections as a uniform granular rock composed of feldspar and hornblende in nearly equal proportions with accessory magnetite.

The feldspar, when fresh, exhibits the multiple twinning of plagioclase. Several observations made on prismatic individuals, which gave symmetrical extinctions on either side of the trace of the twinning plane, gave a maximum extinction angle of 17°, which would place the feldspar near the acidic end of the labradorite series. The feldspar contains clouds of dusty inclusions scattered irregularly throughout its substance. Much of the feldspar is completely decomposed, chiefly to a non-polarizing, kaolin-like mass, more rarely to a brightly polarizing granular aggregate, the nature of which was not determined.

The hornblende is a compact variety of that mineral, green or greenish yellow in color, well marked by pleochroism, cleavage, and extinction. It is always allotriomorphic to the feldspar. Pleochroism is strong, the $\mathfrak{a}$ ray very pale yellowish green, the $\mathfrak{b}$ and $\mathfrak{c}$ rays dark green to yellowish brown, absorption $\mathfrak{a} > \mathfrak{b} > \mathfrak{c}$. The extinction angle c: $\mathfrak{c}$ was observed as large as 17°. Basal sections exhibit characteristic prismatic cleavage of hornblende, and the same cleavage is prominent in longitudinal sections. Irregular scattered grains of magnetite form abundant inclusions in the hornblende. As a rule the hornblende is free from alteration. The only evidence of it observed is a fibration which in some cases affects the whole crystal, accompanied by a change of color to a lighter green, and by a less intense pleochroism.

Magnetite, besides forming inclusions in other constituents of the rock, occurs in large irregular grains having the ordinary properties of that mineral.

In one slide a narrow vein was observed cutting the rock, which was filled with a colorless, transparent mineral in radiating tufts of acicular crystals. It possesses no cleavage, gives brilliant polarization colors, and extinguishes parallel to the prismatic axis. Double

refraction strong and negative. The interference figure is biaxial, and hence the crystals are orthorhombic. Warm concentrated hydrochloric acid failed to gelatinize it, so that it is probably not a zeolite. In all respects except the absence of cleavage the mineral corresponds closely to a colorless anthophyllite, and it is so regarded provisionally.

It is this phase of the rock which exhibits locally the schistose structure before mentioned. In thin sections this structure is expressed by a more or less perfect parallelism of the longer axes of the mineral grains composing the rock. Very little shattering or crushing of the grains was observed, but the banded structure was quite noticeable.

A variety of this type was observed in which the essential constituents are the same as, but the structure is quite different from, that of the type. The structure is ophitic, the lath-shaped feldspars interlacing to form a network filled in with allotriomorphic hornblende. There is also present as an accessory constituent in addition to magnetite, ilmenite in grains and crystals, well marked by its dark color, rhombohedral cleavage, and border of gray leucoxene. The variety thus presents the characteristic appearance of a diabase, in which, however, hornblende takes the place of augite.

The second type presents in thin sections a coarse ophitic to granular structure, thus differing from the first type, from which it also differs in the presence, in addition to feldspar and hornblende, of both orthorhombic and monoclinic pyroxene. The feldspar is for the most part in long and short prismatic crystals, idiomorphic, and with abundant polysynthetic twinning striations of plagioclase. Examined in the same manner as before described, it gave extinction angles uniformly larger than did the feldspar of the first type. The maximum angle was 29°, the average 27°, which indicates its place near the middle of the labradorite series. The general appearance of the feldspar with regard to inclusions and alteration is similar to that of the first type described. In some crystals, however, particularly where the feldspar is in contact with pyroxene, the feldspar is charged with needles of a pale greenish or colorless mineral, apparently secondary, the exact nature of which was not determined.

The larger portion of the hornblende in this type of the rock is identical with that of the first type in structure, appearance, and mode of occurrence. In addition to this there is a fibrous hornblende, generally forming bands or zones about the pyroxene, and certainly of secondary origin. This hornblende is usually lighter green in color than the normal variety, and its pleochroism is less intense. The individuals are of various sizes; sometimes the whole border of a pyroxene crystal consists of one hornblende individual in parallel position to the core, and distinguishable from it by its smaller extinction angle, and by color, cleavage, and pleochroism. More commonly the borders consist of many small shreds and granules, without regular orientation. In all cases the line of contact between the two minerals is irregular but quite sharp, the hornblende penetrating into the cracks and along the cleavage planes of the pyroxene. The hornblende is generally more or less fibrous, but towards the outer portions of the borders it approaches more and more nearly to both the structure and color of the compact hornblende first described, and in some cases the two are only distinguishable by their mode of occurrence.

The evidence is clear that the hornblende is derived from the pyroxene, and the process of alteration may be seen in all stages of completeness, from a narrow zone of hornblende about the pyroxene to an aggregate of hornblende containing shreds and isolated cores of pyroxene with uniform orientation, and ultimately to a simple aggregation of hornblende. In view of these facts the inference is natural that all the hornblende in these rocks is derived by alteration from pyroxene, although in the hornblendic facies first described the change is so complete that no evidence remains of the intermediate steps. It will be seen that the results of chemical analysis tend to confirm this inference.

The orthorhombic pyroxene belongs to the variety hypersthene. It is quite abundant, occurring in grains of considerable size and in granular aggregates. It is transparent, with a reddish color; its surface shows the characteristic high relief of hypersthene; and it is distinctly but not strongly pleochroic, the $\mathfrak{c}$ ray parallel to the prismatic cleavage showing a greenish tint, the $\mathfrak{a}$ ray, at right angles to the cleavage and parallel to $\breve{a}$, a reddish color. The

larger individuals are for the most part of irregular prismatic form, but are without definite boundaries. They possess a distinct cleavage parallel to the greater length of the prism, to which the extinction is parallel. An imperfect parting at right angles to this cleavage is also present. Numerous black rod-like inclusions occur in irregular patches, the longer axes of the rods strictly parallel to the prismatic cleavage of the crystal. Where most numerous the rods give the hypersthene almost a black color, but immediately adjoining such an area may be one entirely free from inclusions. The fine granular aggregates of hypersthene do not exhibit any inclusions, but in all other respects agree with the larger individuals. About most of the larger hypersthene crystals are zones of fibrous green secondary hornblende.

The monoclinic pyroxene is a colorless variety agreeing in character with malacolite. It occurs in irregular grains and in large individuals with more or less definite crystal boundaries. Twins were observed formed according to the usual augite law where the twinning plane is the orthopinacoid. The prismatic cleavage is distinct, but the planes of cleavage are somewhat discontinuous, especially as observed in a basal section. There is also a strong cleavage parallel to the orthopinacoid, which in some cases has almost the character of the pinacoidal parting of diallage. In a section which appeared to be approximately parallel to the clinopinacoid, the angle of extinction on the trace of the cleavage plane was 38°. Being colorless there is no appreciable pleochroism. The pyroxene contains many inclusions in the form of short black rods, which were not identified but may be magnetite. These rods are arranged in zones parallel to the crystallographic planes of the host, the rods lying in two or more intersecting systems in these zones, giving rise in the section to a minute lattice work. There are also irregular grains of magnetite included in the hornblende. The alteration of pyroxene to hornblende, giving rise to borders of hornblende about the pyroxene crystal, has already been described. Alteration also takes place to a fine granular aggregate of brightly polarizing minerals whose nature was not determined.

Magnetite, besides forming inclusions in the other constituents of the rock, occurs in large, irregular grains. Ilmenite is also

quite abundant in this type of rock. Chlorite and limonite occur in very small amount as decomposition products. The former fills interstices among the other constituents as a scaly aggregate, bright green in color, slightly pleochroic, and with faint interference colors. The limonite is mostly disseminated as a pigment but is concentrated in places so as to form opaque yellowish patches.

A chemical analysis was made of the first type or hornblendic facies of the intrusive rock, and the silica was determined in the pyroxenic facies. The results are presented in the accompanying table, together with two other analyses for comparison:—

	I.	II.	III.	IV.
SiO_2	47.41	46.38	51.58	47.38
Al_2O_3	16.03		14.99	16.77
Fe_2O_3	2.66		2.04	4.64
FeO	7.05		8.36	6.73
MnO	trace		trace	.....
CaO	12.33		8.59	10.81
MgO	5.81		6.51	4.11
K_2O	4.47*		.31	.93
Na_2O			3.08	3.02
P_2O_5	trace		.24	.42
TiO_2	1.29		1.05	3.07
H_2O	2.19		3.01	1.25
	99.24		99.76	99.03
Sp. gr.	2.96	3.008		

I. Hornblendic Facies, Epidiorite, Potrero; analyst, C. Palache.

II. Pyroxenic Facies, Hypersthene Diabase, Potrero; analyst, C. Palache.

III. Diorite-Diabase,† Mt. Diablo; analyst, Dr. Melville.

IV. Epidiorite,‡ Eisenbuhl bei Beila.

The silica content of the pyroxenic facies shown in analysis II

*Calculated as Na_2O.

† H. W. Turner, Bull. Geol. Soc. Amer., Vol. 2, p. 387, and W. H. Melville, *ibid.*, Vol. 2, p. 412.

‡ Gumbel, Geognostiche Beschreibung des Fichtelgebirges, Gotha, 1879.

confirms the conclusion reached by the study of its structure and mineralogical composition, that it is a hypersthene diabase. On the other hand, the analysis of the hornblendic facies is that of a more basic rock than its mineralogical composition would lead us to expect. In view of this fact, and of the close agreement between the silica percentages of the two facies, we are again led to the conclusion already reached from field and microscopic study that the two rocks are of similar origin, the hornblende rock being derived from the hypersthene diabase by alteration of pyroxene to hornblende. Hence the hornblendic rocks may be regarded as belonging to Gumbel's class of epidiorites. As will be seen by reference to the table, the analyses of the hornblendic rock of the Potrero, No. I, shows a remarkable similarity to that of a typical epidiorite as given by Rosenbusch, seen in No. IV.

It is interesting to note in this place that a very similar association has been described by Mr. Turner* as occurring at Mt. Diablo. He finds there an area of typical diabase which presents undoubted transitions to a well-defined diorite through paramorphism of the pyroxenic constituent, the two forms having essentially the same chemical composition. The mineralogical composition and alteration of the rocks from the two localities agree closely, and as seen in the analysis quoted above they are closely related in chemical composition. The chief difference noted in the two areas is in the mode of occurrence, the one being a massive outburst, the other a narrow dyke. The hypersthene diabase and epidiorite here described also find a close parallel in the hypersthene gabbro and gabbro-diorite described by Professor Williams† from the vicinity of Baltimore. Slides of typical specimens from that locality were compared with the Potrero rocks and were found to agree closely, particularly with regard to the appearance of the green secondary hornblende. The chemical composition is likewise in close agreement in the two cases.

Relations to Other Formations.—The hypersthene diabase has already been shown to be intrusive into the serpentine, occupying one or more dykes which have been subsequently sheared apart.

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* Loc. cit., p. 387.

† Bull. U. S. Geol. Survey, No. 28, 1886.

Its relations to the San Francisco sandstone are unknown, as it does not appear to intersect that formation anywhere within the limits of the area here discussed.

THE SAN FRANCISCO SANDSTONE.

The San Francisco sandstone is represented in the Potrero by several small patches lying on the flanks of the serpentine mass. It embraces shale, sandstones, and grits of the types common to this formation, and well described by Blake and Newberry, by whom it was named. Associated with the sandstones are two limited areas of the green and red thinly-bedded jaspery rocks, the phthanites of Becker, which are characteristic of this formation in the vicinity of the Bay of San Francisco.

No attempt was made to investigate the stratigraphy of these sedimentary beds, their interrupted and fragmentary character and imperfect exposure rendering such a study almost impossible within the limits of the small area in question. Enough was seen, however, to indicate that they have been folded, and that they do not appear to have undergone extensive metamorphism.

No evidence was discovered bearing on the age of this formation, which was assigned to the Cretaceous by the State Geological Survey on imperfect evidence, and has been since much in dispute.

Geological Laboratory,
University of California, April, 1894.

UNIVERSITY OF CALIFORNIA
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ON A ROCK FROM THE VICINITY OF BERKELEY CONTAINING A NEW SODA AMPHIBOLE.

BY

CHARLES PALACHE, PH. D.

CONTENTS.

INTRODUCTION.

It has long been known that the crystalline schists of the Coast Ranges of California contain in considerable abundance and widely distributed a blue amphibole, related in many of its characters to glaucophane. This fact was first announced by Dr. Becker in his report* on the Quicksilver Deposits of the Pacific Slope, in which he gives brief notes on the characters of the mineral, regarded by him as normal glaucophane. No further published description of this mineral is known to the writer.

In the course of field studies of the crystalline schists in the

*Monograph XIII U. S. G. S., pp. 76, 77, 102–104.

vicinity of Berkeley this blue amphibole was found to be abundantly present, and quite characteristic of these rocks, and it was thought desirable to make a detailed investigation of the petrographical character of one of its occurrences. For this purpose a rock was selected which contained the mineral in unusually well-developed crystals, quite readily separable from their matrix, and, therefore, very favorably situated for study. The result of this investigation was to show that the mineral differed in so many essential points from the other recognized members of the amphibole group as to warrant its consideration as a new species. It is the purpose of the present paper to present the characters of this new amphibole together with a description of the rock in which it was found, the latter being of a quite unique character.

THE ROCK.

The rock in question was found as a large boulder in the bed of a small stream, draining from the west slope of the Contra Costa Hills, about three miles north of Berkeley. Repeated search failed to reveal with certainty the source of this boulder, but closely similar rocks were found in the near vicinity, forming part of the extensive schist complex of the region, and the size and position of the boulder forbid the belief that it had other than a local origin.

Hand specimens of this rock show a distinctly schistose structure, owing to which it splits with great ease into flat slabs. The surface of such a slab is shown in the photograph, Plate 10. On the surface are seen numerous columnar crystals of the dark blue amphibole, embedded in a milk-white granular matrix, which has much the appearance and structure of granulated sugar, and readily crushes to a crystalline powder under the hammer. Minute specks of a pale yellow color are seen abundantly in the matrix. Traversing the boulder in many directions are veins from $\frac{1}{4}$ to $\frac{1}{32}$ of an inch in width, composed of a pale green mineral, coarse granular, with perfect cleavage, and the hardness of feldspar. Where these veins intersect the amphibole crystals, the broken ends of the latter are frequently seen to be connected across the vein by a band of pale green fibrous material which also forms isolated fibrous aggregates in the vein matter.

Cleavage face of the rock, showing the disposition of the blue amphibole prisms in a white matrix of saccharoidal albite. Two veins of more coarsely granular albite charged with actinolite traverse the specimen. Scale, $\frac{4}{5}$ nat.

Constituent Minerals.—The blue amphibole crystals lie with their longest axes in the planes of schistosity, but further than this are not in parallel orientation. They vary in size from the most minute needles to columns 20 mm. or more in length and 3 mm. in diameter; but, as a rule, most of the crystals appearing on any given surface are of the same general dimensions, and decrease in number as they increase in size. The friable character of the matrix renders it easy to extract crystals of the amphibole, and such crystals always exhibit more or less perfectly developed crystal outlines. The forms observed were the prism, ∞P, and the clinopinacoid, $\infty P\grave{\infty}$, the oscillatory combination of which generally produces deeply striated or rounded faces. One crystal was, however, obtained which afforded fairly good reflections in the goniometer, and the angles shown in the accompanying diagram, Fig. 1, were obtained from its measurement. No terminal planes were observed, either macroscopically or microscopically.

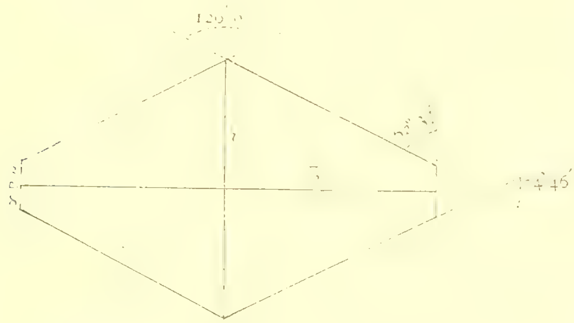

Figure 1.—Showing the values obtained by measurement for the angles indicated in a cross section of the blue amphibole.

Under the microscope the matrix of the rock appears as a homogeneous aggregate of allotriomorphic feldspar grains, very uniform in size and perfectly fresh and water-clear. The grains rarely exhibit any distinct cleavage. Twinning is also very rare, and, when present, follows the albite law. Measurements of extinction angles on such twins give angles averaging 16° on M, indicating that the feldspar is *albite*. The strong resemblance of much

of this feldspar to quartz, in its water-clear character and freedom from cleavage and twinning, leads to a chemical investigation for final discrimination. Fragments tested by Szabo's method of flame tests gave uniformly strong reactions for sodium, and corresponded generally to albite. A portion was freed from amphibole by means of the methylene iodide solution, and found to have a specific gravity of 2.634. A partial analysis of the material thus separated yielded

SiO_2	67.37 %
Al_2O_3	22.01 %
CaO	trace,

figures which, taken together with the facts before presented, prove conclusively that the ground mass is a very pure albite unmixed with quartz.

The feldspar contains numerous inclusions, both liquid and solid. The liquid inclusions are round or angular in form, generally contain bubbles which are sometimes in rapid motion, and are arranged in bands or zones extending from grain to grain, or more frequently are scattered quite irregularly through the feldspar substance. The solid inclusions consist of minute grains and needles of the blue amphibole, grains of magnetite, crystals of zircon, and grains of sphene or titanite. The zircon is distinguished by its characteristic crystal form, high relief, brilliant polarization colors, and parallel extinction. The sphene never shows crystal outlines, but is in irregular grains or granular aggregates, sometimes reaching a diameter of 1 mm., and is very abundant in the rock. It is the material of the yellow specks mentioned before as visible macroscopically. It is colorless or yellowish gray in thin section, with irregular cracks and rarely sharp cleavages, which are generally bordered by a dark gray decomposition product. It exhibits high relief, strong double refraction, and very brightly colored biaxial interference figures. A few grains separated in the heavy solution gave a specific gravity of 3.49, and their solution in sulphuric acid gave a strong reaction for TiO_2, with hydrogen peroxide.

Secondary Veins.—The veins of greenish color appear in thin section as aggregates of large feldspar grains, most of which are simple albite twins, with extinction angles on M of about 16°. The

feldspar is water-clear, and contains many strings and bands of liquid inclusions. Its chief characteristic, however, is the network of needle-like fibers of pale green actinolite which traverses it in every direction, and gives it its green color. It is this mineral which forms the silky bands joining the ends of disrupted amphibole crystals, mentioned above. It will be further considered in connection with the blue amphibole. Flame tests on the vein feldspar yielded results identical with those given by the albite of the matrix, and fragments which were free from actinolite needles gave a specific gravity of 2.623. It may thus also be considered as albite. The boundary between the albite of the matrix and that of the vein can, however, always be sharply drawn. The latter is always much more coarsely granular, generally contains the actinolite fibers, which are never seen elsewhere in the rock, and is quite free from the blue amphibole, from zircon, and from sphene. Fig. 1, Plate 11, shows the sharp contrast between the mass of the rock and the intersecting vein. The veins are clearly secondary, their minerals having been deposited either by segregation or by infiltration into fissures formed in the rock after it had attained substantially its present character.

THE BLUE AMPHIBOLE.

The blue amphibole appears in the thin sections most frequently in sharply bounded lath-shaped crystals of a fine blue or yellowish blue color. It is also seen in irregularly bounded prismatic individuals, and in rounded grains. In sections cut parallel to the schistosity of the rock, transverse sections of the amphibole are never seen, and the forms are uniformly prismatic, with very distinct cleavage cracks parallel to the prismatic axis, and with frequent and, for the most part, sharp, transverse cracks or partings. In sections cut at right angles to the schistosity basal sections of the amphibole abound. They show generally a sharp boundary, with the dominant form a prism, ∞P, of about 126°. The angles of the rhomb are generally, but not always, truncated by the clinopinacoid, and very rarely by the orthopinacoid. Frequently, several crystals are intergrown with the orthopinacoid in common, as

shown in Plate 11, Fig. 2. More rarely they are united on a face of the prism, as in Fig. 2. In basal sections the prismatic cleavage is very clearly marked, giving the rhomb-shaped network so characteristic for amphibole. Twinning has not been observed.

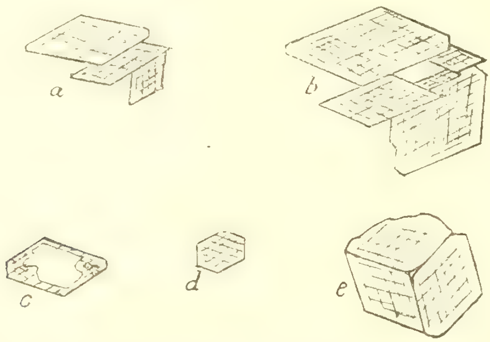

Figure 2.—Showing the forms of cross sections and grouping of prisms of the blue amphibole. In *c* the center of the prism is occupied by albite.

Optical Characters.—The optical investigation of the amphibole is rendered difficult by the intensity of the pleochroism in all sections. The plane of symmetry is the plane of the optic axes, and an axis emerges very excentrically in orthopinacoidal sections. The position of the acute bisectrix, and, consequently, the optical sign of the mineral, was not determined. Repeated measurements of the extinction in sections cut parallel, or approximately parallel, to the clinopinacoid were made with the Bertrand ocular, and the maximum values thus obtained were as follows:—

$13^\circ.3$, 13°, 13°, $12^\circ.5$, $12^\circ.2$, 12°, $11^\circ.5$, 11°, $10^\circ.9$.

We may thus consider the direction of extinction as making an angle of about 13° with the chief crystallographic axis. The axis of elasticity corresponding to this direction of extinction was determined by means of the quarter-undulation mica plate as the axis of maximum elasticity, $\mathfrak{a}$. This orientation of the elasticity axes appears to be the most important optical character for the determination of this mineral. It places it in close relation to riebeckite, which alone of all the amphiboles possesses this optical orientation. Although the observation could not be made in this mineral, it

must be assumed that in it, as in riebeckite, the axis 𝔞 lies in the obtuse angle of the crystallographic axes, and hence we have the formula, b = 𝔟, c : 𝔞 = 11°–13° in front.

The pleochroism is very strong; 𝔞, sky blue to dark blue; 𝔟, reddish to purplish violet, very dark in basal sections; 𝔠, yellowish brown to greenish yellow, never colorless. Absorption formula, $\mathfrak{a} \gtreqless \mathfrak{b} > \mathfrak{c}$, 𝔞 and 𝔟 being somewhat variable in the relative intensity of their colors. These colors are in all cases more intense than are those of typical glaucophane from various localities examined by the writer. They approximate in intensity the pleochroic colors of riebeckite. They are shown in Plate 11, Figs. 2–9, as they appear in the three principal sections of the mineral.

Not infrequently the pleochroism reveals a zonal structure of the amphibole in which the center of the crystal has a lighter, more greenish color, and a larger extinction angle than the rim. In a clinopinacoidal section of a zoned crystal the outer portion was found to extinguish at 12°, the inner greenish portion at 17° to the cleavage. Plate 11, Fig. 3, exhibits a basal section of such a zoned crystal. This zonal structure is probably due to a local predominance or concentration of the actinolite molecule which, as will be shown later, plays an important part in the composition of this mineral.

The blue amphibole frequently contains interpositions consisting of grains of feldspar and sphene and minute zircon crystals. The whole center of an amphibole crystal may be filled with feldspathic matter (Fig. 2*c*,) and the extremities of the crystals are frequently frayed into brushes or finger-like projections, between which the feldspathic matrix penetrates.

A healing or enlargement of broken amphibole crystals by secondary actinolite has been mentioned on a previous page. Such crystals occur abundantly in sections which intersect any of the veins which traverse the rock. The actinolite may either completely reunite the crystal fragments, as shown in Plate 11, Figs. 6 and 7, or it may project into the vein as a fringe on the broken ends of the crystals, as shown in Plate 11, Figs. 1 and 8. It is rarely or never seen on any portion except the ends of the amphibole crystals. The actinolite is in exceedingly fine fibers, pale green in

color and pleochroic. Its fibration is always parallel to the chief axis of the amphibole crystal to which it is attached, and the two minerals are in parallel position and in crystallographic continuity. Measurements for extinction of clinopinacoidal sections of amphibole and attached actinolite showed for the former an angle of 13°, for the latter 17°–18°. The optic orientation is normal, $b=\mathfrak{b}$, $c:\mathfrak{c}=$ 17°–18° behind. The pleochroism is in shades of green. The absorption formula is $\mathfrak{c} \geq \mathfrak{b} > \mathfrak{a}$.

Chemical Characters.—The amphibole was separated from the rock by means of Klein's solution for chemical analysis. The powder thus obtained was examined under the microscope, and found to be quite free from attached feldspar. Single fragments thus obtained gave a specific gravity of 3.16, while a solution in which part of a large number of fragments fell, and part floated, gave 3.126. These figures may be considered as limits for its specific gravity. Before the blowpipe fragments melt readily to a grayish magnetic bead, and afford a strong flame reaction for sodium. The hardness of the mineral is between 5 and 6, and its streak a pale blue.

For the following chemical analysis the writer is indebted to Mr. W. S. T. Smith. It was executed on some two grammes of carefully purified material, in the mineralogical laboratory of the University of California:—

				Atomic Quotients.	Atomic Ratios.
SiO_2	55.02	Si	25.71	.9182	21.35 say 21
Al_2O_3	4.75	$\overset{\cdots}{\mathrm{Al}}$	2.52	.0932	2.17 " 2
Fe_2O_3	10.91	$\overset{\cdots}{\mathrm{Fe}}$	7.46	.1335	3.11 " 3
FeO	9.46	$\ddot{\mathrm{Fe}}$	7.36	.1317	3.07 " 3
MnO	trace	..	....	....	....
MgO	9.30	Mg	5.58	.2331	5.37 " 5
CaO	2.38	Ca	1.70	.0426	1.00 " 1
Na_2O	7.62	Na	5.66	.2459 }	5.83 " 6
K_2O	.27	K	.23	.0058 }	
H_2O	undet.	O	43.21	2.743	63.99 " 64
	99.70		100.00		

From the atomic ratios found in the last column the following formula is derived:—

$Na_2Al_2Si_4O_{12}$—Glaucophane molecule.

$2[Na_2\dddot{Fe}_2Si_4O_{12}]$—Riebeckite molecule.

$9[\ddot{R}SiO_3]$—Actinolite molecule.
where $R = Mg : Fe : Ca = 6 : 2 : 1$

In this formula the ratio of $\dddot{Fe}$ to Fe is made 4 : 2 instead of 3 : 3, as found in the analysis, and Mg is taken as 6 instead of 5.

In the following table are presented typical analyses of glaucophane and of riebeckite, together with the analysis of the Berkeley mineral:—

	Glaucophane.*	Riebeckite.†	Berkeley Amphibole.
SiO_2	55.64	50.01	55.02
Al_2O_3	15.11	.....	4.75
Fe_2O_3	3.08	28.30	10.91
FeO	6.85	9.87	9.45
MnO	.56	.63	trace
MgO	7.80	.34	9.30
CaO	2.40	1.32	2.38
Na_2O	9.34	8.79	7.62
K_2O	......	.72	.27
	100.78	99.98	99.70

Classification.—Comparing these analyses we see that the Berkeley mineral occupies a mean position between the other two, having less alumina than glaucophane, less iron than the riebeckite, and more of the monoxide bases than either. This relation is well expressed in the formula given above, in which we see that the sesquioxide bases are divided between one glaucophane and two riebeckite molecules, and the abundant monoxide bases appear in a proportion of the actinolite molecule larger than is normal for either glaucophane or riebeckite.

It thus appears that we have in this mineral an amphibole

*O. Luedecke, Z. d. Geol. Ges., XXVIII, 1876, 249.

†A. Sauer, Z. d. Geol. Ges., XL, 1888, 138.

related in its optical properties to riebeckite, and sharply defined from glaucophane, and in chemical composition lying between riebeckite and glaucophane. It is very interesting to note that an amphibole occupying just this position, so far as optical characters are concerned, has been recently described by Dr. Whitman Cross* as occurring in the form of a secondary growth on pyroxene in an altered dyke rock in Custer County, Colorado.

For convenience of comparison a table has been prepared showing the properties of the Colorado and the California amphiboles, and also of glaucophane and riebeckite:—

Mineral.	Pleochroism.	Optical Orientation.	Opt. Sign.	Specif. Grav.	Ratio of Bases.
Glaucophane.	$\mathfrak{c}$ = blue. $\mathfrak{b}$ = reddish violet. $\mathfrak{a}$ = colorless to yellowish. $\mathfrak{c} \geq \mathfrak{b} > \mathfrak{a}$.	$b = \mathfrak{b}$ $c : \mathfrak{c} = 5^\circ$ behind.	—	3.1	$Na : \dddot{R} : \ddot{R}$ 1 : 1 : 2
Riebeckite.	$\mathfrak{c}$ = green. $\mathfrak{b}$ = blue. $\mathfrak{a}$ = deep blue. $\mathfrak{a} > \mathfrak{b} > \mathfrak{c}$.	$b = \mathfrak{b}$ $c : \mathfrak{a} = 5^\circ\text{-}7^\circ$ front.	?	> 3.3	2 : 2 : 1
Blue amphibole (Colorado).	$\mathfrak{c}$ = pale yellow. $\mathfrak{b}$ = purple to violet. $\mathfrak{a}$ = deep blue. $\mathfrak{a} > b > \mathfrak{c}$.	$b = \mathfrak{b}$ $c : \mathfrak{a} = 13^\circ\text{-}15^\circ$ front.	?	?	?
Blue amphibole (Berkeley).	$\mathfrak{c}$ = brown to greenish yellow. $\mathfrak{b}$ = reddish to bluish violet. $\mathfrak{a}$ = deep blue. $\mathfrak{a} \geqq \mathfrak{b} > \mathfrak{c}$.	$b = \mathfrak{b}$ $c : \mathfrak{a} = 13^\circ$ front?	?	3.16	1 : 1 : 3

A glance at the table shows the almost perfect identity of the optical properties of the last two minerals, as well as their differences as compared with the others. In the absence of chemical investigation of the Colorado amphibole, and, despite the totally different paragenesis of the two minerals, their optical similarity may be accepted as proof of their identity; and, as the present investigation establishes it as a new species, it seems desirable to

* Note on some Secondary Minerals of the Amphibole and Pyroxene Groups, *Amer. Jour. Sci.*, XXXIX, May, 1890.

the writer that a name should be assigned it. He therefore proposes for it the name of Crossite, which will serve to commemorate the discovery of the mineral by Dr. Cross.

CONCLUDING REMARKS.

It is believed that the mineral here described is a type of much of the blue amphibole of the Coast Ranges. The writer hopes in the near future to extend his study of this and allied soda amphiboles of this region and determine, if possible, to what extent and in what manner they vary, and what their distribution is.

In conclusion the writer would express to Prof. A. C. Lawson, under whose direction these investigations were carried out, his sincere thanks for ever-ready advice and aid. He desires, also, here to thank Mr. W. S. T. Smith for the chemical analysis herewith presented, and Dr. H. Lenk, of Leipzig University, for kindly aid rendered in the determination of some of the optical properties, and in the calculation of the formula.

June 21, 1894.

EXPLANATION OF PLATE 11.

FIGURE 1.—Cross section of vein traversing the rock. The rock is a fine granular aggregate of albite, with large blades of blue amphibole *c*, scattered grains of sphene *s*, and occasional crystals of zircon *n*. The vein is a coarse granular aggregate of albite *f*, traversed by crystals of actinolite *a*, which for the most part are secondary enlargments of the blue amphibole and in crystallographic continuity with it. × 10.

FIGURE 2.—Showing parallel growth of a group of crystals of blue amphibole. × 30.

FIGURE 3.—Showing zonal composition of blue amphibole with predominance of the actinolite molecule at the center. × 30.

FIGURES 4 AND 5.—Transverse sections of prisms of blue amphibole showing color of the $\mathfrak{c}$ ray. × 30.

FIGURE 6.—Section parallel to $\infty P \bar{\infty}$, showing color of $\mathfrak{b}$ ray. × 15.

FIGURE 7.—Section parallel to $\infty P \bar{\infty}$, showing color of $\mathfrak{a}$ ray. × 15.

FIGURE 8.—Section parallel to $\infty P \grave{\infty}$, showing color of $\mathfrak{a}$ ray. × 30.

FIGURE 9.—Section parallel to $\infty P \acute{\infty}$, showing color of $\mathfrak{c}$ ray. × 30.

FIGURES 6–9 also show, on a larger scale than Figure 1, the secondary enlargements of actinolite upon the broken ends of the blue amphibole.

NOTE.—No attempt is made to indicate the pleochroism of the actinolite, which is comparatively feeble.


2
3
4
5
6
7
8
9
1
f
c
a
N

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THE GEOLOGY OF ANGEL ISLAND

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CONTENTS.

GENERAL STATEMENT OF THE GEOLOGY.

ANGEL ISLAND, lying about three and one-half miles north of the city of San Francisco, is the largest and most diversified of the several small islands scattered about in San Francisco Bay. It is separated from Tiburon Peninsula, the nearest mainland, by Raccoon Strait, a passage about half a mile in width in its narrowest part, and with a maximum depth of thirty-nine fathoms.

In shape, the island approximates somewhat roughly to an equilateral triangle with sides about one and a quarter mile in length, and embraces an area of about one square mile. The northwest side, defined by Points Stuart and Campbell, forms the southeast shore of Raccoon Strait.

The topography, as the map shows, is comparatively simple, the island having a central summit 771 feet* in height, from which radiate the various spurs. Two of the latter, namely, those extending out to Point Campbell and to Point Ione, dominate the others, and form what might be called a crescentic backbone to the island,—a term the appropriateness of which will be more manifest when the geologic structure is discussed.

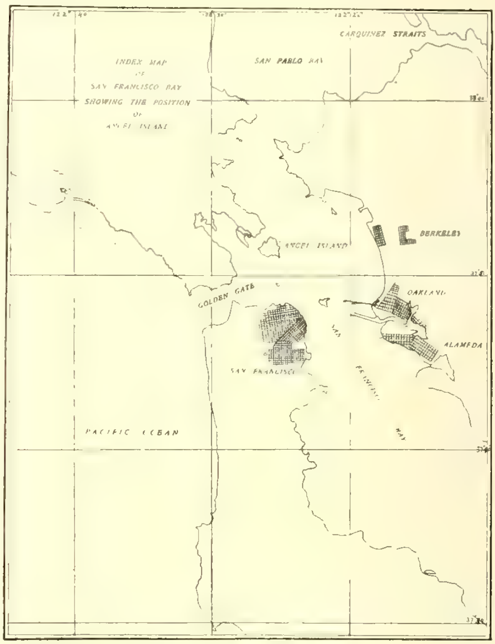
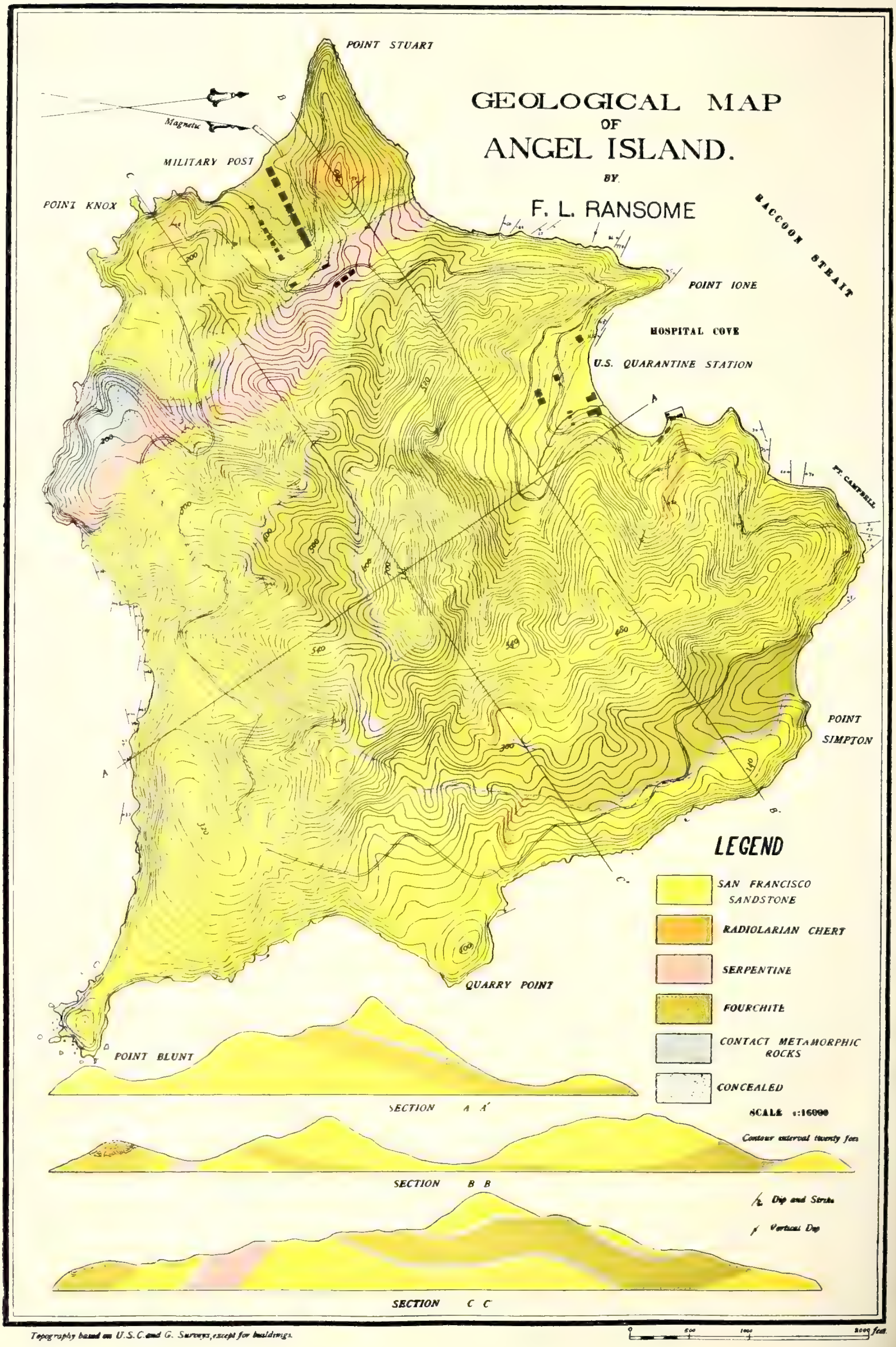


Figure 1—Index Map.

By far the larger portion of the island is made up of the San Francisco sandstone, the general disposition of the beds being that of a synclinal trough with its axis pitching approximately northwest, so as to tilt the trough toward the strait. A glance at the map shows that this structure is suggested topographically by the crescent-like ridge just mentioned, and geologically by the almost concentric band of eruptive rock presently to be described.

Intimately associated with the sandstone are several small areas of what in a former paper were termed "bedded jaspers," but which, for reasons to be presented later, it seems preferable to designate by the name of "radiolarian chert."

*Pacific Coast Pilot, U. S. Coast and Geod. Surv., 4th ed., 1889, p. 183.


GEOLOGICAL MAP
OF
ANGEL ISLAND.
BY
F. L. RANSOME
POINT STUART
MILITARY POST
POINT KNOX
RACCOON STRAIT
POINT IONE
HOSPITAL COVE
U.S. QUARANTINE STATION
PT. CAMPBELL
POINT SIMPTON
QUARRY POINT
POINT BLUNT
LEGEND
SAN FRANCISCO SANDSTONE
RADIOLARIAN CHERT
SERPENTINE
FOURCHITE
CONTACT METAMORPHIC ROCKS
CONCEALED
SCALE 1:16000
Contour interval twenty feet
Dip and Strike
Vertical Dip
SECTION A A'
SECTION B B
SECTION C C
Topography based on U.S.C. and G. Surveys, except for buildings.

The curved belt of eruptive rock (fourchite) shown on the map is the exposed edge of an intrusive sheet or sill, that has followed very roughly the general bedding of the sandstone, and has given rise to more or less continuous zones of locally intense contact metamorphism, adjacent to its upper and lower surfaces. On the western side of the island there also occur extensive exposures of eruptive rock, which is in part identical with that just mentioned, but which passes also by insensible gradations into glassy and feldspathic facies, and even into a breccia, showing that it was erupted at no great depth below the then existing surface. As would be expected from this latter fact, the contact metamorphism is in this case not so pronounced, and is mainly confined to the cherts, which seem to be peculiarly susceptible to such alteration. Small, sporadic intrusions of eruptive rock occur in many places in the sandstone, each producing more or less accompanying alteration. As these small intrusive masses are petrographically identical with various facies of the sill rock, it is believed that they were erupted contemporaneously with the latter, and are products of the same original magma.

The most conspicuous, and, in many respects, the most interesting geologic feature of the island, is the large serpentized dyke that cuts across its western half in a northwest and southeast direction.

Its fantastically weathered outcrops, projecting from the soil-covered hill slopes, form a striking feature in the landscape, and, together with numerous loose blocks and boulders, define its course as a broad gray band stretching over hill and dale. The fact that this serpentine has plainly resulted from the alteration of a dyke of basic igneous rock, lends a strong local interest to the occurrence on account of the persistency with which the view that the greater part of the serpentine of the Coast Ranges is metamorphosed sediments, still retains its place in the literature, confusing and obstructing the way toward a clear understanding of the geology of this region.

Of far more general interest than the preceding, however, is the pronounced contact metamorphism that has been effected by the rock of which the serpentine is a derivative, and by the fourchite, upon the cherts and sandstones through which they forced their

way. The metamorphism is remarkable alike for its intensity and for the mineralogical simplicity of the resulting rocks. It will be shown that the latter, in their typical development, consist almost wholly of holocrystalline glaucophane schists, and, furthermore, that these schists appear to present no essential differences, when derived from the sandstone, from those formed by the metamorphism of the chert. Lastly, the schist produced by contact metamorphism alongside the serpentine, has not been found to present any real distinctive feature to differentiate it from that adjacent to the fourchite. The conclusion from this fact is, that the unknown causes that have led to the development of glaucophane as the most conspicuous contact mineral are not confined to any single rock, but must be dependent upon the common properties of at least two of them,—the chert and the sandstone, or the serpentine and the fourchite,—while it is quite probable that if either of these two binary groups had been replaced by another rock or group of rocks, the resulting metamorphism would have been of a different character.

THE SEDIMENTARY FORMATIONS.

The San Francisco Sandstone.—The San Francisco sandstone has been described as occupying the larger portion of the island. At Quarry Point, where considerable quantities have been taken out for building purposes and for use in government harbor improvements, it is a hard stone of fairly homogeneous texture, and bright gray color, the latter weathering to a yellowish brown on exposed outcrops. The most noticeable constituents to the unaided eye are occasional flakes of mica, and numerous sharply angular fragments of a very fine black shale. Under the microscope the rock appears as a wholly unaltered sandstone. A close study of the component grains reveals their very heterogeneous character. Besides the quartz grains, plagioclase occurs in great abundance, usually in fairly fresh granules showing numerous polysynthetic lamellæ. Then follow, in about the order of their frequency, fragments of chert, small scales of allogenic muscovite, angular splinters of black shale with fine quartz-filled cracks, bits of some glassy basic eruptive, and, lastly, of some finer grained sandstone. A chemical

examination showed that the rock contains only 70.5 *per cent* of silica, and is accordingly very far from being a pure quartzose sandstone. The rapid disintegration of this rock, when employed as a building stone in San Francisco, is doubtless due to the relative abundance of the plagioclastic and other non-quartzose granules.

At Quarry Point the sandstone lies in very massive beds, but this appears exceptional. From Point Blunt westward to the serpentine, the exposures along the shore generally show very thin beds or laminæ, separated by slight partings of shale. In these sections there is little or no conglomerate, although higher up on the hill, just below the intrusive sill, some of the beds become quite pebbly. Similar pebble bands outcrop on the beach, about half way between the north end of the serpentinized dyke and Point Ione. The pebbles are usually disposed as bands in the sandstone, and not as separate sharply defined beds. They are generally rather flattened and of all sizes up to ten inches (25 centimeters) in diameter, and four inches (10 centimeters) thick. They consist of quartz, dark chert, basic eruptive, sandstone, and a peculiar holocrystalline rock showing idiomorphic decomposed feldspars. The last is very abundant, and is remarkable for containing fine needles of a blue amphibole apparently identical with that presently to be described, but which cannot have had a contemporaneous origin with it. The rock from which the pebbles are derived has evidently been considerably altered, but is not known to occur *in situ*.

Certain portions of the sandstone, notably that exposed between Point Blunt and Quarry Point, contain numerous fragments of chert, identical with certain varieties of the bedded cherts of the sedimentary series. These fragments are derived from some pre-existing terrane of cherts, the occurrence of which in place is not yet known. At certain places, also, cherty bands, from a fraction of an inch up to three inches (7.5 centimeters) in thickness, occur in the sandstone, parallel with the bedding of the latter. This is well shown on the western side of Point Ione, where they form numerous thin parallel bands on a cliff section of rather massive sandstone.

All the sandstone on the island, with the exception of that at Quarry Point, and possibly a few of the thicker beds elsewhere, is

characterized by a more or less distinct shear structure, parallel with the original bedding planes. This is often not very pronounced, and appears to be unaccompanied by any chemical alteration except near the contact with intrusive rocks.

Owing to the discontinuous nature of the rock exposures over the interior of the island, it was not possible to select any characteristic bed upon which to construct a stratigraphic series. The thick beds of Quarry Point are, however, regarded as forming the base of the series exposed, being succeeded by the thinner beds and conglomerate bands, the last named being in the upper portion. It is believed that 2,000 feet is a very conservative estimate for the thickness of the sandstone beds exposed upon Angel Island; the true figure is probably in excess of this. There has been considerable disturbance in the strata, as would be expected from their pre-Tertiary age and from the extensive scale upon which local igneous intrusion has taken place. Consequently the structure is somewhat obscure. In a general way, however, the beds may be regarded as forming a deep syncline with its axis running about northwest and southeast; the mapping, moreover, seems to indicate the presence of a subordinate buckle, or low anticlinal ridge, occupying the bottom of the trough. This syncline is tilted up so as to slope to the northwest, and the semicircular amphitheatre rising above Hospital Cove is a feature conditioned by structure and revealed by erosion. That the syncline is not a simple fold is readily seen by reference to the dips and strikes plotted upon the map, which plainly show the existence of minor corrugations, but the recognition of its presence as a broad structural feature is the simplest construction to be put upon a stratigraphy whose minuter structure is hopelessly intricate.

The whole series of sandstone beds bears evidence of a rapid and variable accumulation, which probably accounts for the absence of fossils, no trace of animal remains having been found in them.

The Radiolarian Chert.—Interbedded with the sandstone, and occurring in small isolated patches within it, are numerous masses of the ordinary jaspery rocks usually associated with the San Francisco sandstone. Although in many localities the name "bedded jaspers" may be applied to these rocks with perfect propriety, yet the investigation of their representatives upon Angel Island, appears

to indicate that "radiolarian chert" is, on the whole, a better designation for them, inasmuch as it casts some light upon their origin, and suggests their relationship with similar cherts in Europe.*

The most instructive exposure of these cherts occurs on the eastern side of Hospital Cove, as a bedded formation interstratified with the sandstone, and running from the water's edge up into a little cañon, where it appears to terminate rather abruptly. The change of sedimentation from sandstone to chert appears at this point to have been somewhat gradual, as the two are not sharply defined at the contact. Several facies can be distinguished in the chert beds. There is the common red jasper with the usual quartz veining, also a light-colored variety, full of tiny cavities averaging about half a millimeter in diameter and lined with iron oxide. A careful search was made for radiolaria in this rock. They were found in abundance in the beds just described, being best preserved in portions having a dark red color and dull earthy fracture, in which they are sometimes barely discernible with a good lens. Some microscopic slides, and additional chips, were forwarded by Professor Lawson, with some specimens of his own from another locality, to Dr. Hinde, and the results of his examination have been appended in a note which he very kindly placed at Professor Lawson's disposal. Having found the remnants of siliceous organisms in the less siliceous portions of the cherts, they were subsequently recognized in the more silicified facies as little spherical bodies of clear cryptocrystalline silica, possessing more or less definite boundaries. From the wavy extinctions observed upon turning the stage between crossed nicols, it is supposed that the silica is in the form of chalcedony. It is possible, if not probable, that, although the radiolaria are best preserved in the more earthy and less siliceous portions of the rock, they were originally much more abundant in the jaspery varieties, but have there become obscured by the solution and recrystallization of the abundant silica furnished by their remains.†

*See appendix by Dr. Geo. J. Hinde, p. 235.

† NOTE.—Becker probably refers to these radiolarian remains in certain of his "phthanites" when he says: "The most interesting constituents of foreign origin are round spots, which often retain evidences of organic character. Professor Leidy, at my request, has examined some of the thin sections containing such spots, which he regards as probably foraminiferous shells." Quicksilver Deposits of the Pacific Slope. Monog. XIII, U. S. Geol. Surv., p. 108.

Whatever may be the source of the silica forming the cherts and jaspers in other portions of the Coast Ranges, on Angel Island it appears unnecessary to call upon any hypothesis of a general secondary silicification to explain their origin. It is a more simple, and, in the light of the foregoing facts, a more probable supposition that they were *originally* siliceous deposits, the silica being derived largely from organic remains and varying in amount in different portions of the series, both vertically and horizontally, with the former abundance or scarcity of the siliceous organisms. When these were few, the non-siliceous components of the deposit would predominate and furnish a dark matrix for the preservation of the radiolaria. When, on the other hand, the latter were very abundant, the deposit would be largely opaline silica, in a condition susceptible to solution, and the organic structure would become obliterated.

Both the sandstone and the chert have been locally metamorphosed by invading eruptive rocks, but these alterations will be described under their appropriate heads.

THE FOURCHITE.

Occurrence.—It is only for want of a better name to apply to the eruptive rock now to be described, that the writer has adopted the above designation, being confronted with the difficulty of naming a rock that is unquestionably a geologic unit, and at the same time exhibits facies which, when separately considered, would receive distinct petrographic names. It will appear that the name is applicable only to the deeper-seated and more central portions of the larger rock masses, and could not be applied to their peripheral modifications, nor yet to the smaller isolated apophyses were they considered as distinct occurrences. There has even been some doubt as to the fitness of applying the name "fourchite" to the main igneous masses, as they appear to present certain differences from the typical fourchites described by Williams;* on the other hand, they would seem to fall most readily into this group, and the observed differences are not of a sufficiently pronounced character to justify the introduction of a new rock name.

*The Igneous Rocks of Arkansas, Annual Rept. Geol. Surv. of Ark. for 1890, Vol. II, p 107, *et seq.*

The largest mass of fourchite occurs in the form of the intrusive sheet or sill, already referred to as invading the San Francisco sandstone. There are no satisfactory exposures of the contact between the eruptive and the sandstone, but the irregular shape of the former, and the accompanying contact metamorphism, prove it to be a true sill and not an interbedded flow.

Another mass of considerable size occurs to the west of the serpentinized dyke, and is most conspicuously exposed in the bluffs near Point Stuart, where it weathers to a characteristic rust-brown color. Its intrusive character is plainly shown, both near Point Stuart and Point Knox, by the presence of abundant altered inclusions of chert, and by actually observed igneous contacts. The best example of the latter may be seen on the beach to the northeast of Point Stuart. The hill, of which the point is a part, is capped by a mass of the thinly bedded chert resting upon the fourchite. This mass of strata has been deformed and twisted by the intrusion, so that a portion in which the beds have been thrown nearly vertical, continues down the northern slope of the hill to the water's edge, at which the eruptive rock can be seen in sharp igneous contact with the chert, and crowded with disrupted fragments of the latter. The alteration brought about in the chert at this point will be described in detail in the sequel.

Between the wharf of the military post and Point Knox, the eruptive rock presents several facies. Portions consist of a breccia others show an imperfect spheroidal structure, while still others appear to be identical with the massive fourchite of the sill. These different varieties cannot be sharply differentiated; they were evidently all simultaneously formed during one period of intrusion. The spheroidal facies appears to be intermediate between the brecciated variation and the ordinary fourchite.

The metamorphic action of the eruptive west of the serpentine is everywhere much less intense than that brought about by the sill rock to the east, indeed, it often seems to be wholly absent or confined to mere mechanical disturbance. This fact, taken in connection with the presence of brecciated and glassy facies, indicates that this portion of the fourchite was intruded much closer to the then existing surface than that forming the large sill; yet the abso-

lute identity of the holocrystalline augitic facies of the two masses is fair evidence that both are genetically connected, and were probably also at one time continuous across the space now occupied by the serpentine dyke.

Of the various smaller isolated masses of eruptive rock shown on the map, all of which are regarded as apophyses from the same igneous mass that gave rise to the sill, by far the most interesting is that of Point Blunt. The waves have here washed away much of the soil, and reveal the most unmistakable case of an intrusive contact between the eruptive rock and the sandstone and chert. Portions of the intruding rock, moreover, show in moderate perfection the peculiar spheroidal structure described by the writer in the basalt of Point Bonita, proving conclusively that such structure cannot be rigidly restricted to surface flows, although it is still believed that lavas exhibiting it must have been erupted under very nearly surface conditions. The radiolarian chert has been broken through, as well as the sandstone, and a prominent stack just southwest of the point, is a mass of the spheroidal eruptive thickly crowded with inclusions of the red and the green chert, which, however, exhibit but slight evidences of alteration. The mechanical results of the intrusion upon the sandstone are glaringly apparent in an intense local crushing, followed by much secondary calcification, as well as in a darkening in color. The microscope shows that important chemical alteration has also been brought about, the description of which will follow in its proper place.

The various smaller intrusions of the fourchite indicated upon the map do not call for detailed description. An interesting fact was observed, however, in the case of the two minute patches on the shore just north of Quarry Point; both of these contain included fragments of bright red chert, although the latter rock is not exposed *in situ* except at some little distance to the west, and considerably higher up on the hill.

Petrographic Character.—Throughout the greater portion of the sill, as observed on the horseshoe-shaped exposure passing around the island, the fourchite preserves a fairly uniform character. It is rust-brown on weathered surfaces, but dark gray on fresh fracture showing a compact texture, which under the lens appears to be fine

granular. The component minerals, with the exception of scattered specks of pyrite, cannot be made out without the microscope. In thin section (Pl. 13, Fig. 1) the rock is seen to be made up almost entirely of augite, in irregularly bounded grains, with a subordinate amount of interstitial groundmass.

The augite never shows complete crystallographic boundaries, and is usually in the form of rather rounded, irregular grains. It is colorless, or has a very slight brownish tinge, and shows the usual high relief. The double refraction is strong and its character positive. The dispersion is $\rho > v$. The prismatic cleavages are never very distinct, but can usually be detected in the larger grains, in which cases the direction of extinction is nearly always inclined to them, or bisects their angles. The maximum extinction angles appear to lie between 40° and 45°. The grains are occasionally twinned, sometimes repeatedly so, resulting in two halves, separated by several narrow lamellæ. Each grain generally possesses an independent optical orientation, except in occasional cases in which the separating material consists of a secondary blue amphibole presently to be described.

The contrast between this nearly colorless augite of Angel Island and the violet-red pleochroic augite of Point Bonita, is rather noteworthy, when there is taken into consideration the fact that the eruptive rocks of each locality are intimately associated with the same sedimentary strata, and are accompanied by nearly identical spheroidal facies. From the constant character, extending over wide areas, generally possessed by the augite in the eruptive rocks belonging to any one petrographic province,* it might have been supposed, *a priori*, that violet-red pleochroic augite would be found on Angel Island; but such has not turned out to be the case.

The groundass, which forms quite a subordinate part of the rock, is seen with low powers to consist of smaller granules of augite, and a very fine polarizing matrix. With a No. 8 Hartnack, however, this matrix resolves itself into a dense matted aggregate of small, stout, colorless prisms, which are themselves sometimes imbedded in a small quantity of a yellowish green substance which appears nearly or quite isotropic. In section the prisms are usually

*Iddings, Origin of Igneous Rocks, Bull. Phil. Soc., Wash., Vol. 12, p. 130.

short lath-shaped, with the ends either squarely truncated or rounded. The form of the cross sections could not be made out with certainty, but some were apparently square. The index of refraction is high, and the relief considerable. The double refraction is in general low, the interference colors being gray or yellow, but varying somewhat, and becoming more brilliant in certain slides. The extinction appeared to be strictly parallel with the sides of the prism, and the largest individuals gave an interference figure, which, while indistinct on account of their small size, appeared to be unmistakably biaxial. The mineral therefore probably belongs to the orthorhombic system. By using the quartz wedge it was ascertained that the prismatic axis could *not* be the axis of least elasticity. Cleavage was not detected with absolute certainty, yet by careful focusing, with high powers, it is possible to distinguish a breaking up of the light, as if from very fine cracks, and in one or two cases extremely fine lines parallel with the prismatic axis appeared to be visible. There is exhibited, also, an irregular transverse parting in many of the prisms. The crystals showed no signs of gelatinization when treated with warm hydrochloric acid.

The secondary nature of this mineral was, by the study of certain peripheral facies of the fourchite, placed beyond reasonable doubt. Certain local, and more or less glassy, variations of the fourchite contain large phenocrysts of plagioclase, often corroded and irregular in outline. When the original feldspar still remains, these porphyritic crystals show the usual twinning lamellæ of plagioclase, but in by far the greater number of cases they have changed into an aggregate composed mainly of the prismatic mineral just described, with small amounts of a greenish amorphous substance. In some slides these phenocrysts are so irregular in outline, and so completely altered to aggregates, that their original feldspathic character would have remained extremely doubtful had not other sections shown individuals which revealed at the same time remnants of the plagioclase twinning lamellæ and the development of very minute prismatic microlites. It thus appears that the small crystals occurring so abundantly in the groundmass of the fourchite may, in certain cases, originate from the breaking down of a plagioclase feldspar, and are presumably secondary, in

which case they agree more closely with zoisite than any other known mineral. Whether the prisms forming the greater part of the fourchite groundmass were actually derived from the decomposition of plagioclase, it is impossible to say, as no trace of the original mineral remains; but the fact that they do not occupy distinct crystallographic areas is rather against such a hypothesis. It is this uncertainty in regard to the original character of the groundmass that makes the designation of the rock as a fourchite rather a tentative one. The fact that the Arkansas fourchites contain porphyritic crystals of augite, while the Angel Island rock does not, is also a point of difference, but would hardly seem to be an essential one. It is quite possible that future investigations may bring to light many non-porphyritic fourchites, in which case the present typical Arkansas rock would be more aptly designated as a fourchite-porphyrite. Moreover, reverting again to the groundmass, we are told that "in the typical Arkansas fourchites, J. F. Williams seldom found a true glass, and he even found some plagioclase that he regarded as secondary,"* while in the fourchite dyke described by Kemp and Marsters in the Lake Champlain region, "the base is not always, and in fact seldom, a true glass, but contains many colorless, minute acicular crystals of parallel extinction. These are probably nepheline.† The mineral matter containing them shows frequently a feeble refraction, and so, although in other respects resembling glass, it is not perfectly isotropic."‡ In view of the foregoing variations described in the base of the typical rock by the authors cited, it seems justifiable to apply the name fourchite to the Angel Island occurrence, it being an intrusive rock intermediate in texture between the effusive augitites on the one hand and the plutonic pyroxenites on the other.

In considering the advisability of extending the name fourchite to all facies of the intrusion, much weight was assigned to a statement

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* Kemp and Marsters, The Trap Dikes of the Lake Champlain Region, Bull. U. S. G. S. No. 107 (1893), p. 36.

† Is it not possible that the mineral here tentatively referred to nepheline is really identical with the small prisms determined as zoisite in the Angel Island fourchite?

‡ *Ibid.*, p. 36.

by Williams, in which he says, "The trap (fourchite) shows considerable variation in different parts, both in its texture and in its mineralogic constituents, so that, petrographically considered, it should be classed under several heads."*

A very noticeable feature in these sections of the fourchite is the presence of a bright blue amphibole, having the pleochroism of glaucophane, which appears to have been developed secondarily, partly at the expense of the augite. It is often in the merest films, occupying interstitial spaces, or filling cracks in the grains of augite. With very high powers, however, these films can generally be seen to be made up of aggregates of extremely delicate needles, having a generally parallel arrangement. At other places portions of the augite grains have been wholly replaced by the blue amphibole. In such cases the fibers or needles of amphibole appear to be generally parallel with the prismatic axis of the augite. The alteration differs from ordinary uralitization in being comparatively superficial. The greater part of a grain of augite will be perfectly fresh and unaltered, while the amphibole bounds it peripherally, occupies some corner, or extends into the cracks in the crystal. Moreover, the resulting hornblende is not confined within the original boundaries of the augite, but spreads out into the interstitial spaces between the grains, and even forms small, though well defined, prisms, with somewhat fibrous structure and ragged terminations, which are not in direct contact with any augite. In general, however, it forms irregular filmy areas, which only under high power show a parallel fibrous arrangement. The most common pleochroism is from a brilliant ultramarine blue to a rich violet. Less frequently a light yellowish-green color is observed. The extinction angle is small, certainly less than ten degrees. From its similarity to some of the glaucophane of the contact metamorphic rocks, it is probably the same mineral, but may quite possibly belong to some closely related member of the blue amphibole series. It does not appear to have originated wholly from the augite, although it often replaces the latter mineral. Its formation was probably contemporaneous with that of the zoisite prisms, and it may have been formed in part from the same unknown mineral as the latter.

*Igneous Rocks of Arkansas, Ann. Rept. Geol. Surv. of Arkansas for 1890, Vol. II, p. 30.

Becker,* in describing the alteration of the augite of his "pseudo-diabase," which he regarded as a metamorphosed sediment, mentions the fact that "the uralite often has a bluish tint approaching that of glaucophane." There can at present be little doubt of the true eruptive character of the so-called "pseudo-diabases," in which case the mineral observed by him was very likely the same as that just described.

The fourchite is characterized by being remarkably free from the usual accessory minerals of basic eruptive rocks. Many slides show no magnetite, and apatite has not been detected, although the chemical analysis (I of the table of chemical analyses, p. 231) shows a small amount of phosphoric acid. Its specific gravity is 3.20.

In spite of the general uniformity of the fourchite composing the sill, there are, nevertheless, a few departures from what has been described as the typical rock. A specimen taken from the western limb of the outcrop, at a point about two hundred yards southeast of where the line of section C C′ (Plate 12) crosses it, shows a greenish, decomposed rock, which under the microscope is seen to consist of a glassy groundmass with felted lath-shaped feldspars, in which are imbedded large phenocrysts of plagioclase, apparently much clouded and decomposed. Under high power these large feldspars are seen to be crowded with extremely minute prisms of the mineral which has been referred to zoisite. No augite is visible in the slide. Also on the 360-foot contour, due north of the central summit of the island, and therefore on the upper edge of the V-shaped band of fourchite above Hospital Cove, a decomposed glassy facies was observed, which, however, was too much obscured by decay for satisfactory microscopic study.

Turning now to the area of eruptive lying west of the serpentine, no such general persistence of character is to be found as exists in the mass just described. Immediately under the capping of chert on the south side of Point Stuart Hill, and along the beach immediately north of Point Knox, the rock is macroscopically identical with the fourchite of the sill. Under the microscope they differ very slightly from the typical facies of the latter, the augite exhibit-

*Quicksilver Deposits of the Pacific Slope, Monog. XIII, U. S. Geol. Surv., p. 75.

ing a tendency to take on lath-shaped forms, and the groundmass containing a noticeable amount of glass. Both contain scattered patches of pyrite, and the Point Knox rock shows some iron ore accompanied by gray cloudy leucoxene. The blue amphibole already described in the sill rock is also present in all slides from this area in which the augite is well developed.

Near the extreme end of Point Stuart, specimens of the eruptive may be taken only a few yards apart which show complete gradations between the usual granular, augitic fourchite, containing no glass, and a highly glassy facies, in which no complete crystal forms are visible. In the various intermediate stages the augite loses its granular form and takes on an elongated habit, the crystals showing a tendency toward radial and brush-like groupings. Plagioclase also appears, both as porphyritic crystals and in the usual lath-shaped forms, but is always much decomposed. Nearly all slides, both from the Point Stuart and the Point Knox area, show the presence of the small prismatic crystals of zoisite, either in the groundmass or in the altered porphyritic plagioclases.

The most glassy facies yet found is represented by a small hand specimen, collected by Professor Lawson at the base of the cliff near the extremity of Point Stuart. In general color and appearance this glassy form is not very different from the rest of the fourchite, but a close examination of its weathered surfaces with a lens, indicates that it is finely spherulitic. A thin section, under the microscope, shows that it is made up of small, roughly polygonal areas abutting against each other and separated by what appear to be shrinkage cracks. Each polygon is surrounded by a border of varying width of a yellowish brown polarizing material, which is apparently radially fibrous, the fibrous extinguishing at considerable angles between crossed nicols. This translucent brown material, which is probably a mixture of augite crystallites and glass, sometimes fills the whole polygonal area, but more often the center is occupied by a gray cloudy substance, almost dark between crossed nicols, which was at first taken for unindividualized glass, but which appears to be a secondary product resulting from the decomposition of bunches of radiating plagioclase microlites, although it may also be partly original glass. The specific gravity

of this glassy facies is decidedly high, being 3.08, whereas the basalt glass of Sorne which is mentioned by Judd and Cole* as being exceptionally high, is only 2.89. As the specific gravity of the fourchite is 3.20, the difference between its specific gravity and that of the glassy facies is not greater than that often found between a rock in its crystalline and its glassy conditions.

A brecciated facies has previously been referred to as occurring in the cliffs along the beach just south of the military barracks. This consists of small fragments of eruptive rock, generally rather angular in shape, and held together in a matrix of still smaller particles. Inclusions of chert are quite frequent, and generally bear evidence of having experienced some mechanical force, and exhibit a certain amount of alteration. A similar breccia also occurs in smaller amount near the end of Point Stuart. In both cases these breccias are plainly contemporaneous facies of the intrusive fourchite with which they occur, and a subaerial origin for them is put out of the question by the fact that, both near Point Stuart and Point Knox, the whole mass of the eruptive rock of which they are a part is capped by considerable masses of chert that have been heaved up and altered by the intrusive igneous mass. Moreover, near the small chapel which stands upon the hillside south of the military post, a small dyke, coming from the same eruptive body of which the breccia is a part, can be seen cutting through the sheared and disturbed sandstone.

It thus appears that, under certain circumstances, of which it is rather difficult to form a mental picture, a rock may be intruded in a brecciated condition, and the same statement holds, of course, in regard to the spheroidal facies, with which the breccia is most closely associated, and which has previously been shown to be compatible with intrusion at Point Blunt. It is incredible, however, that such rocks could have been intruded at any considerable depth. They cannot have been subjected when in a molten or plastic state to the pressure of thick overlying strata, and it is equally clear that they must have cooled with comparative rapidity. It appears highly probable that they represent material that has been sub-

*On the Basalt-glass (Tachylyte) of the Western Isles of Scotland, Q. J. G. S., Vol. XXXIX, 1883, p. 450.

jected to explosions and attrition within one or more of the vents through which portions of the fourchite magma found their way up from below.

Mention has already been made of the interesting nature of the igneous intrusion at Point Blunt, and the interest is not diminished when the eruptive rock is studied under the microscope. A specimen taken near the southwestern corner of the point does not differ at first glance from the fourchite of the sill, but the lens shows that it contains small lath-shaped sections of feldspar. Under the microscope it might be classed as an ordinary diabase. The lath-shaped plagioclases predominate in well-developed crystals, showing twin lamellæ, while the augite is rather subordinate in amount. The latter is inclined to be granular in form, and is identical with the augite of the sill. Magnetite is abundant, and there is also considerable chlorite and calcite present. The rock has a specific gravity of 2.97. This facies may be regarded as a connecting link between the fourchite as it occurs in the sill, and the rock next to be described.

The spheroidal eruptive, previously referred to as forming a conspicuous stack just off the point, and accessible at low water, is a dense, greenish rock, showing no distinct macroscopic crystals. In thin section (Pl. 13, Fig. 2) it affords the most beautiful example yet seen, of the brush-like grouping of slender plagioclase crystals which was described in a former paper as characteristic of similar dense green eruptive rocks with spheroidal structure, occurring at Point Bonita, Mount Diablo, and elsewhere. The plagioclase crystals take on various forms. Sometimes they are slender needles sharply pointed at both ends; sometimes lath-shaped with frayed and bristling ends. Delicate skeleton crystals, consisting of two long parallel needles connected at their middle points, are abundant. Many of the slender crystals show in perfection the beautiful brush-like wisps described in the paper referred to. With nicols crossed, it is seen that the feldspar microlites and crystals are largely decomposed, but enough of the original substance remains to show their feldspathic character. Some of the broader, lath-shaped sections show distinct twinning lamellæ. Certain brown brushes, whose fibers extinguish at large angles, and show fairly bright polarization

colors, have been referred to augite; they form, however, but a small part of the rock. The larger part of the slide is occupied by a cloudy gray glass. The specific gravity of the rock was determined to be 2.80, it being somewhat lighter than the preceding.

Contact Metamorphism.—If, as seems most probable, all the eruptive rock of the island, with the exception of the serpentine, is the product of one eruption, then a study of the map is enough to demonstrate its intrusive character. But additional evidence on the latter point is amply supplied by the pronounced alteration that the invading rock has produced in the sedimentary formations through which it forced its way. Where the alteration has been most complete, the resulting rock is in general a holo-crystalline blue-amphibole schist. As the existing literature on Coast Range geology makes no mention of "glaucophane schists" arising from local contact metamorphism, and generally assigns them, together with the radiolarian cherts and much of the serpentine, to wide-spread regional metamorphism, the results arrived at in this paper have been to a certain extent forced upon the writer against certain preconceived notions drawn from reading. Consequently, more than usual care has been taken in establishing what, from the mapping alone, would in ordinary cases be accepted as a true zone of contact alteration. One familiar with the geologic conditions about San Francisco Bay will readily understand that nothing like a continuous belt of schist is exposed along the contact between the fourchite and the sandstone. On the contrary, in walking along the boundary line between the two rocks, the schist is encountered in isolated masses of varying sizes, outcropping above the soil, and in loose fragments, so disposed as to indicate the presence of a narrow zone of the same rock beneath. Such outcrops are rigidly confined to a narrow strip between the sandstone and the fourchite, or they are entirely surrounded by the latter. In no single instance has any schist been found upon the island that does not bear the above relation either to the fourchite or the serpentine. Furthermore, although the former has broken through the sandstone and contains abundant inclusions, they are all more or less perfect amphibole schist, and an included fragment of sandstone is unknown except in the case of one or two very small sporadic intrusions

already mentioned, where the invading mass was too insignificant to bring about much alteration in the surrounding strata. It will be seen, on turning to the map, that there are numerous and considerable breaks in the continuity of the metamorphosed zones. In the greater number of cases this merely indicates that no schist outcrops from the soil, although it may be present beneath it. In one or two instances, however, in which the contact between the fourchite and the sandstone has been exposed, the alteration has not gone far enough to obliterate the ordinary clastic structure of the latter, and appears to be confined to a crushing, darkening in color, and extensive veining with calcite or quartz. Only such portions have been mapped as metamorphic rock as have actually been more or less recrystallized or in which there is good reason to suppose such action has taken place. It will be apparent from the foregoing that the island does not afford good opportunity for studying the various steps of alteration at varying distances from the igneous mass. It is possible, however, to demonstrate its existence and to indicate its character.

The most interesting mass of schist exposed upon the margins of the large fourchite sill is indicated upon the map, on the upper side of the eastern limb of the crescent-like exposure. A single mass, of perhaps five feet in diameter, here shows three facies of very different appearance, according as different minerals predominate in each. Portions are often brilliantly white, with a granular, saccharoidal texture, evidently made up chiefly of feldspar, in which are disseminated a few scales of brown mica and needles of blue amphibole. In other portions the amphibole is much more abundant, giving the rock a bright blue color, and still others are dark brown from the preponderance of the brown mica. The different colored bands are often quite sharply separated from each other. A portion of the rock, showing all three minerals mentioned, was sliced and placed under the microscope. It shows large crystals of blue amphibole, generally without regular crystallographic terminations, and usually clustered into aggregates, lying in a clear, colorless matrix.

Cross sections of the amphibole show, besides the dominant prismatic faces, a slight development of the macropinacoidal and

clinopinacoidal faces. The usual prismatic cleavage is distinct in all sections, those perpendicular to c showing the characteristic hornblende angle. The maximum extinction angle observed was about 7° to the prismatic cleavage, the angles in general being much smaller. The relation of the axes $c: \mathfrak{c} = 7°$, and $b = \mathfrak{b}$ was determined by means of the quartz wedge, and confirmed by the mica plate. The strong and beautiful pleochroism is very noticeable, $\mathfrak{a}$ being light greenish yellow, $\mathfrak{c}$ indigo to ultramarine blue, and $\mathfrak{b}$ a rich violet. The absorption is $\mathfrak{c} > \mathfrak{b} > \mathfrak{a}$. Sections from the orthodiagonal zone, showing blue and violet pleochroism, give a biaxial interference figure in convergent light, with a small axial angle. The optical character is negative. The interference colors are only fairly brilliant in rather thick slides. Some crystal fragments were picked out from the powdered rock and treated with hydrofluosilicic acid in accordance with Boricky's method, and yielded abundant crystals of the sodium fluosilicate, together with some gelatinous alumina, and possibly a very few crystals of the silicofluoride of calcium. From the foregoing optical and chemical properties the mineral may be safely classed as glaucophane.

Dr. Chas. Palache* in a recent number of this BULLETIN has described a new mineral from the vicinity of Berkeley, intermediate in chemical composition between glaucophane and riebeckite, and having an optical orientation similar to the latter. The paragenesis of the two minerals is practically the same in both cases, which lends additional interest to the fact that they are distinct. It may be stated that the general appearances of the two minerals under the microscope are very similar. They differ slightly, however, in shades of pleochroism and in the colors between crossed nicols.

The colorless groundmass of the rock is seen, with crossed nicols, to be composed of closely-fitting grains of plagioclase. These grains are perfectly fresh and clear and generally without twinning. When twins occur it is most commonly in the form of simple halves, or rarely three or more lamellæ are present, twinned according to the albite law. The extinction angles average about 15° as a maximum on either side of the composition plane in sym-

*On a Rock from the Vicinity of Berkeley, Containing a New Soda Amphibole. This BULLETIN, Vol. I, pp. 181–192, Pls. 10 and 11.

metrical sections. This plagioclase is undoubtedly albite. Quartz is wholly absent in this facies of the rock.

The brown mica is in thin scales, often collected into wisps and tufted aggregates. It has a bright chestnut-brown color, with a strong absorption parallel with the cleavage. Cleavage flakes show a biaxial figure with a very small axial angle, the center of the cross barely opening.

Garnets are thickly scattered through the slide as inclusions in the albite and glaucophane. They rarely exceed 0.1 mm. in diameter, and are usually much smaller. They have a very faint rose tinge, and when one can be found occupying the full thickness of the section, it is isotropic. The index of refraction is very high.

There are present, also, a few irregular grains of a mineral having a higher index of refraction than the garnets, and of a faint yellowish or gray color. With nicols crossed no marked change is made in the colors of the grains, and the extinctions are not sharp, owing to the diffusion of light that accompanies a high refractive index. Some grains show a biaxial interference figure, with numerous brilliantly colored rings. The dispersion is $\rho > v$ and the optical character positive. The mineral is without doubt titanite, and appears to be identical with that described by Palache in the Berkeley rock.

A portion of the schist was powdered and the minerals separated by Klein's solution. A large portion of the feldspar fell at about 2.7 sp. gr., leaving the rest suspended. The heavier portion had a slight pink tinge, and when the grains were examined under the microscope, they were seen to contain abundant crystals of garnet, in the form of apparently unmodified rhombic dodecahedrons. Their color in incident light is a faint pink or wine yellow. The grains of albite are perfectly clear, with a vitreous luster, and at least one perfect cleavage. Many show the striations due to polysynthetic twinning. A qualitative examination of the pure white feldspar powder, having a specific gravity of about 2.6, showed the presence of silica, soda, and alumina, with a trace of iron, and no lime or magnesia. It is therefore a very pure albite.

Another facies of the contact zone outcrops near the eastern end of the strip shown on the map, just south of, and below, the summit of the island. This rock, too, has a white granular groundmass,

which is thickly speckled with flakes of brown mica. The granular matrix has not, however, the dazzling whiteness of the albite, but has the more vitreous appearance of quartz. Glaucophane is here very subordinate, occurring only in occasional radiating tufts of small crystals.

Under the microscope the colorless groundmass, or matrix, turns out to be composed entirely of interlocking grains of clear quartz, without any feldspar. Brown mica is abundant, sometimes in isolated scales but more often in sheaf-like bundles. Garnets are particularly plentiful, and in certain parts of the slide cluster into dense aggregates. They are all of small size, the largest observed being about 0.1 mm. in diameter. Titanite occurs very sparingly. One acutely rhombic section was noted about 0.2 mm. in length, of a faint brown color, and showing a perceptible absorption parallel with the shorter diagonal of the rhomb. Crystallographic boundaries are, however, very rare, the mineral usually occurring in small highly refractive grains, traversed by comparatively coarse and irregular cracks.

In the single strip of schist of which the foregoing rock forms a part, there is considerable variety to be observed. Near its middle part a schist outcrops having a green color, and brilliant with scales of white mica. The microscope shows it to be mainly composed of a colorless mica, having the optical properties of muscovite, and a green pleochroic mineral in granular aggregates, which appears to be hornblende. It is biaxial, and appears to have oblique extinction. The pleochroism is from a bright green to yellow green. The colors between crossed nicols are about equal to those of hornblende. The absence of crystal form and of distinct cleavages renders the determination doubtful. Chlorite, brown mica, and calcite are also present. It was thought that the colorless mica might be paragonite, but it gave a distinct flame reaction for potassium and is probably muscovite.

About a hundred yards west of the foregoing rock several pieces of schist were picked up containing visible garnets, but the latter were wholly decomposed, and this particular facies was not exposed *in situ*.

The discovery of perfectly crystalline schists apparently result-

ing from the alteration of sediments by intruded igneous rock, stimulated search for rocks showing the intermediate stages of metamorphism. As might be supposed, this effort met with more success in the case of the smaller isolated masses of eruptive, and in the areas west of the serpentine dyke, than in the main fourchite sill, both from the fact that the metamorphic action did not proceed so far, and that they have been better exposed through wave action.

A piece of the sandstone, from near the contact with the intrusive rock of Point Blunt, was selected for examination. It does not differ much in color and general appearance from the fresh unaltered sandstone of Quarry Point. But close inspection, more particularly of the weathered surface, shows that it has been profoundly squeezed, and is somewhat veined with calcite. Under the microscope it exhibits an ideal sheared structure imposed upon the ordinary sandstone. The original clastic structure is still clear, and fragments of black shale and eruptive rock can be plainly recognized. But along the numerous shear planes, have been developed delicate wisps of brightly polarizing white mica (muscovite). With nicols crossed, it is seen that much of the original clastic material has recrystallized into a fine mosaic, composed probably of quartz and feldspar, and the formerly rounded grains have taken on fantastic corroded forms. Fine needles of blue amphibole are quite abundant, generally clustered into pale blue or lilac-colored aggregates. Zoisite is fairly abundant in small prismatic individuals without distinct terminations. They often have a conspicuous transverse parting. It is colorless, with a high index of refraction and consequently strong relief. The double refraction is very weak. The extinction is in every case parallel with the prism and the interference figure biaxial. The habit in general is very similar to that of the zoisite in the fourchite groundmass. Some long jointed prisms also occur, however, resembling closely those figured by Becker.*

Glaucophane in irregularly bounded crystals and bundles of fibers was also found in other places near the contact with the fourchite, in sandstone which macroscopically appears but little altered.

*Quicksilver Deposits of the Pacific Slope, Monog. XIII, U. S. G. S., p. 78, Fig. 1, *d*.

All the chert resting upon the fourchite to the west of the serpentine, has been more or less altered. That least affected is on the hill east of Point Stuart, about in the center of the mass. Pieces were collected here having a light yellowish-gray color, with a rather schistose fracture, and showing a very fine granular texture with no particular luster. Under the microscope it shows evidence of pressure and shearing. It is composed of little spherical bodies of comparatively clear cryptocrystalline silica, which in size and shape exactly resemble the radiolarian remains already described, lying in a darker less transparent matrix. The conclusion is easy and natural, that this rock represents a chert which, originally rich in radiolaria, has been subjected to intense pressure. The little spherules of pure silica being more resistant than the inclosing matrix, have been crowded together, while still preserving their form, and the matrix has been forced to recrystallize in the shearing planes. Under high powers, the cloudiness of the matrix is seen to be due to a thick dusting of minute crystal needles and granules, but they are much too minute for identification.

Another specimen, taken near the former, has a thoroughly jaspery look and a splintery fracture. Under the microscope, and with high power, it is seen to be composed of closely fitting grains of recrystallized quartz, through which are strewn microlites of nearly colorless amphibole, in slender, acicular forms, and also, what is apparently the same mineral, in short, stout prisms without crystallographic terminations, and having a light yellowish tint. The stouter microlites have a tendency to cluster together, forming nuclei from which the longer needles project. Other microlites and grains appear to be present, but were not identified.

Upon turning to the map, it will be seen that the cherts, which crown the hill of Point Stuart, run down to the beach on the north as a narrow ledge, the bedding planes being tilted up at a steep and variable angle. Immediately at the beach, the fourchite is very clearly intrusive into the cherts, penetrating the latter irregularly and being full of detached inclusions. The chert bears evidence of strong crushing and subsequent resilicification and veining. Close to the contact the chert has taken on the characteristic blue tint that invariably serves as an indication of the presence of glauco-

phane.* Under the microscope, a slide made from a fragment taken immediately at the contact, shows a holocrystalline glaucophane schist, but of very fine texture, and traversed by numerous veins of clear crystalline quartz. With a No. 8 Hartnack objective, the glaucophane appears as small, slender, many-jointed prisms. The large ones show the characteristic pleochroism, but this is fainter in the more minute, and is not visible at all in the smallest and thinnest individuals. Other minerals may be present with the glaucophane, but, from the similarity of habit of all the prisms, this is not very likely. These minute crystals are thickly crowded in a fine mosaic of crystalline quartz, and possess a generally parallel arrangement, so that aggregates of the prisms sometimes give the pleochroism that is not perceptible in the single individuals. The slide still shows traces of the original radiolaria in a mottled appearance, caused by the numerous spots of relatively clearer quartz. The boundaries of these circular spots are shadowy, and merge into the rest of the groundmass.

Similar evidences of alteration may be observed in the cherts near Point Knox. A specimen from the central part of the chert area, is a variegated jasper with splintery fracture. Under the microscope it reveals a clear ground of quartz, crystallized into a fine mosaic, through which are scattered abundant small crystals of some mineral in slender-jointed prisms, with pointed and frayed ends. The interference colors are fairly bright, and the index of refraction high. The crystals are nearly colorless, but, when matted into aggregates, are greenish yellow. Owing to their small size, it is difficult to observe their extinction angles accurately. Although most extinguish apparently parallel, some show small angles. The mineral is probably a light-colored amphibole, but its determination is not certain. It resembles some of the smaller microlites found in the glaucophane schists.

Near the fourchite this chert also assumes the blue tint indicative of the presence of glaucophane. An inclusion in the eruptive on

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*Note.—It is quite possible that some of the acicular crystals of blue amphibole occurring in the contact rocks are not truly glaucophane, but some other soda amphibole. It is thought, however, that the use of the name *glaucophane*, with this proviso, is preferable to the cumbersome repetition of *blue amphibole* in order to avoid a possible misnomer.

the beach about five hundred feet south of the wharf, having a bright blue color, with a very dense jaspery texture, was examined microscopically. It proved to be a mass of glaucophane microlites and recrystallized quartz, the former so small and so thickly crowded that the highest power can only resolve them in the thinnest edges of the section. Possibly other minerals are present, but these two are the only ones recognized. Scattered through this dense groundmass are numbers of the small circular areas of clear quartz, which have been identified as the probable remains of radiolaria. These are fringed and transfixed by the sharp needles of glaucophane projecting into them from the groundmass.

THE SERPENTINE.

Occurrence.—As has previously been indicated, this rock occurs as a large dyke traversing the western portion of the island, and attaining in its broadest exposure a width of over five hundred feet. In its northern portions it stands out boldly above the surrounding soil as a massive belt of ragged gray fragments and jutting outcrops. Toward its southern end, however, the dyke loses prominence and finally pinches out in a little ravine, reappearing again in an extensive outcrop just beyond, and also in three places along the shore to the west of the main exposure. That a dyke of such size should really be discontinuous at the point indicated upon the map is extremely improbable. It is a more reasonable supposition that the original top of the dyke was not far from its present exposed surface, and that at the point where the map shows an apparent break, its original top has never been revealed by erosion. It is easy on such a hypothesis to account for the several small exposures of serpentine, and for the wide extension of the metamorphic rocks about the southern extremity of the dyke. The altered rocks can be regarded as resting upon the serpentine, the latter being at no great depth below.

The trend of the dyke is nearly northwest and southeast, and its hade, as revealed by the mapping, and indicated by certain rough laminations within its mass, though probably very variable, is to the southwest, at a maximum angle of about 35°. Its northeasterly boundary is marked by a fairly simple line of contact with

the sandstone, but the southwesterly, or upper side, is defined by a line of greater complexity; moreover, several smaller outcrops occur on this side, which are superficially isolated from the main dyke.

Petrographic Character.—Macroscopically, the serpentine possesses peculiarities which the writer has not observed elsewhere,—not even in the serpentine at Tiburon, on the other side of Raccoon Strait, which is apparently continuous with that of Angel Island. A weathered block resembles at first glance a coarse conglomerate, although pebbles and matrix appear of the same color. Closer inspection shows at once that the whole rock is serpentine, and is made up of hard, compact nodules, ranging in size from an inch to a foot in diameter, imbedded in a softer, much sheared matrix. When one of the nodules is broken, it is seen to be composed of a very pure, homogeneous serpentine, green-gray in color, translucent, and breaking with a splintery fracture. The texture appears to be very fine saccharoidal or granular, to compact. Small black specks of magnetite and chromic iron are scattered sparingly through the mass. The lens shows generally no trace of crystals, beyond here and there a glistening needle or fiber. The cause of this nodular structure is very clearly internal movements, whereby the whole serpentine mass has been sheared and slickensided throughout, the harder portions remaining as rounded and polished nodules. A serpentine showing a somewhat similar nodular structure has been described by Palache* at the Potrero, San Francisco. The spheroids in the latter rock are larger than those at Angel Island, the matrix is more crumbling, and the serpentine itself is somewhat different. There can be no doubt, however, that the origin of the structure is the same in both occurrences. One can hardly study the serpentinized dyke upon the island without being impressed by the great discrepancy between the amount of internal movement shown by its present structure, and the extent to which similar shearing can be proved to have affected the adjacent rocks. This would seem to suggest that the increase of bulk brought about by the serpentinization of the original dyke rock may have been an active cause of the pressure and shearing.

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*The Lherzolite-Serpentine and Associated Rocks of the Potrero, San Francisco. This Bulletin, Vol. I, No. 5, p. 164

Under the microscope the rock shows a somewhat cloudy, colorless substance, speckled with grains and irregular aggregates of magnetite. With crossed nicols, the colorless groundmass is resolved into a confused aggregate of serpentine in lamellæ, fibers, and grains, polarizing in low tints of gray and yellow. Occasionally the fibers are arranged at right angles to each other, giving suggestions of the "grate structure," but it never goes farther than a suggestion. A few remnants of large crystals of some brightly polarizing mineral with pronounced cleavage and inclined extinction are also present, and have been determined in fresher specimens as diallage. An analysis of the serpentine of one of the harder nodules is given in column II of the table of analyses (p. 231). During the chemical examination, it was found that some of the supposed grains of magnetite were not decomposed by acids, and gave a distinct chromium reaction in the borax bead. On the other hand, the microscopic slides show none of the brown translucent chromite that is to be seen in the serpentine from Tiburon.

Although the foregoing may be taken as a general description of the serpentine, there is more or less variation observable in the mass. Some slides consist almost wholly of serpentine in finely felted fibers, others show varying amounts of magnetite and perhaps chromic iron, and some contain remnants of pyroxene crystals. No olivine has been detected in any of the sections, nor can the former presence of rhombic pyroxene be shown with certainty.

At the northern extremity of the dyke, down on the beach, the rock exhibits a different facies from that previously described. It is here much less sheared and the nodular structure is absent. On fresh fracture it shows numerous brilliant cleavage faces of some light-colored pyroxene, in crystals of 10 mm. or so in length. This rock is clearly but slightly serpentinized, and represents a comparatively little altered facies of the original dyke rock from which the serpentine has been derived.

Under the microscope it shows a holocrystalline allotriomorphic granular structure, and is made up of large interlocking areas of diallage, which is colorless in thin section, and shows the usual brilliant interference colors and high relief. Some few sections show all three cleavages, but the prismatic cleavage is usually

rather indistinct and interrupted. That parallel with the orthopinacoid, on the other hand, is sharply marked by numerous bold straight lines. The maximum extinction angle observed made an angle of 44° with the prismatic and orthopinacoidal cleavages, and several observations gave readings close to this angle. Careful search in two slides failed to reveal the presence of any olivine or rhombic pyroxene, nor was any indication of the "mesh structure" visible in the serpentine, which probably makes up from one-fourth to one-fifth of the slide, and has evidently resulted from the alteration of the diallage. Although in some few instances a crystal of diallage may be observed permeated through and through with the serpentine, only a mere skeleton of the brightly polarizing pyroxene remaining, yet this is comparatively rare. The crystals are usually fresh and uncracked, and the serpentinization has been confined to their peripheries. Magnetite, and possibly chromite, occur very sparingly as original inclusions in the diallage, but, on the other hand, they are often very abundant in the accompanying serpentine. This fact, taken in connection with the manner in which the strings of magnetite granules arrange themselves with reference to the boundaries of the irregular areas of serpentine, shows that these minerals are mainly secondary, having been formed from the excess of iron and chromium oxides present in the pyroxene molecule and not required in the formation of serpentine.

There can be little doubt that the whole of the serpentine has been derived from a holocrystalline igneous rock composed wholly or mainly of diallage. Fragments of this rock are not confined to the northern end of the serpentine area, but have been found in two other places near the middle portion of the dyke. It would be a little unsafe to say that the rock just described is *identical* with that which has furnished most of the serpentine, since its present fresh condition may signify that it was a somewhat local facies, and thus was not so susceptible to change as the rest of the rock. But that the difference was not great, and that this facies is capable of transformation into serpentine indistinguishable from the main mass, is certain.

Contact Metamorphism.—The contact phenomena of the serpentine are of the same general character as those of the fourchite, but

a peculiar feature in the case of the former, is the intensity and extent of the metamorphism on the western side of the dyke, and the general absence of conspicuous alteration upon the eastern side. The present hade of the dyke is to the southwest, and consequently the most intense metamorphism has taken place on its upper side. It is possible that the inclination was at one time greater than at present, which might account for the observed difference.

Following closely the western margin of the dyke, as it outcrops on the surface, is a fairly continuous strip of dark blue schist, of varying width, and showing slight petrographic modifications from point to point. A typical specimen taken close to the thumb-like projection on the west of the main body of serpentine shows a fine gray or brownish matrix crowded with slender glistening crystals of dark steel-blue amphibole. These interlace in all directions, but the majority have their longer axes nearly parallel and give to the rock its schistosity. A section cut at right angles to the direction of schistosity (Pl. 13, Fig. 4) shows abundant cross sections, with a few longitudinal sections of the amphibole prisms, imbedded in a fine crystalline mosaic, which is probably largely albite, although some quartz may be present. Thin, irregular flakes of brown mica are abundantly scattered through the groundmass. The sections of amphibole transverse to the prism show the usual hornblende angles, and, when large enough, the characteristic cleavage of the group in a series of fine-shaped lines. A peculiar and striking feature of these cross sections is a frequent zonal structure similar to that described and figured by Palache.* When the shorter diagonal of the rhomb is lying parallel with the shorter diagonal of the polarizing nicol, it shows an outer rim of a light greenish yellow tint, surrounding a center which is either of lighter hue or colorless. In a position at right angles to the above, the outer shell becomes a deep blue or violet, with a strong absorption of light, while the central portion becomes light green, with little or no greater absorption. The two portions of the crystal are generally well marked off. The inner portion is characterized by abundant fluid inclusions, both with and without bubbles. The zonal structure is also frequently shown in the longitudinal sections, a strip of the green amphibole

Loc. Cit., p. 187, Pl. 11, Fig. 3.

being bordered on either side by the blue. The pleochroism of the inner strip in such cases is light greenish yellow to colorless transverse to the prism, and light green parallel with it. Its angle of extinction is also greater than that of the blue amphibole, often being as great as 20°, while the latter seldom exceeds 6°. By no means all of the crystals are so zoned; many are composed throughout of the blue variety, although never of the green. A parting of the long prisms transverse to the longer axis is very common, and the different portions have frequently been displaced and the intervening spaces filled in with the crystalline groundmass. In such cases the broken ends of the prismatic sections are often tipped with the blue amphibole in a manner indicative of replacement rather than secondary growth or enlargement.

The blue amphibole, so conspicuous in this schist, is apparently glaucophane, as in the case of the schist adjacent to the fourchite. The mica plate shows that the axis of least elasticity corresponds with the crystallographic *c*, and the angle of extinction does not exceed 7°. In other slides, however, larger angles have occasionally been noted, and it is quite possible that more than one species of blue amphibole occurs on the island. In the case of the serpentine contact zone, the mineral doesnot occur in a condition so favorable for investigation as it does next to the fourchite sill, and its specific determination in every slide would be a matter of considerable difficulty, if not an impossibility. The green amphibole may be simply classed as actinolite.

Schist, generally similar to that just described, borders also the western edge of the large southern division of the dyke, and accompanies the smaller exposures along the shore to the west. Near the most northerly of these three smaller areas, the schist has a decidedly knotty, or conglomeritic, appearance. The whole is now perfectly recrystallized, but the "pebbles" are harder and more dense than the matrix, and stand out on weathered surfaces. If, as is barely possible, these were originally water-worn pebbles, they have been squeezed and flattened out of their former shape. In general they can be knocked out of the matrix, and the latter is usually more rich in brown mica immediately surrounding them than elsewhere.

Inclusions of the schist are frequent in certain portions of the serpentine, especially in the small area just referred to, where several occur of large size. Smaller fragments are also visible in the cliff section at the extreme southern end of the main dyke.

Although the whole area between the various outcrops of serpentine just referred to near the south end of the dyke is mapped as metamorphic rock, yet it is not all of the character just described. Away from the immediate contact with the serpentine, it is a greenish gray, schistose rock, with a fine granular texture and vitreous, rather greasy, lustre. When exposed on the beach it is seen to form thick beds made up of numerous thin laminæ, parallel with the planes of schistosity. The dip and strike of these beds, and, in fact, their general appearance at a little distance, correspond closely with that of the thinly laminated sandstone to the east of the serpentine. Under the microscope, the rock shows the usual finely crystalline mosaic, in which both feldspar and quartz occur; the former, however, seems to predominate. Scattered through this matrix are a few crystals and bunches of glaucophane. With a high power, a certain cloudiness in the groundmass resolves itself into innumerable crystal grains and needles. The latter in general show the pleochroism and extinctions of a light green actinolite, and give to the rock its slight greenish tinge.

The eastern side of the serpentinized dyke shows, as has been stated, far less evidence of metamorphic action than does the western. Nevertheless, at both ends of the dyke, where it is exposed through wave action, alteration can readily be made out, and the probabilities are that a zone of contact metamorphic rock borders the eastern edge also, but is concealed by the soil.

At the southern extremity of the dyke, the rock immediately adjoining the serpentine on the east is a light-greenish schist, with fine granular texture and oily lustre, standing in nearly vertical layers. These layers or laminæ appear to represent the original bedding planes of the sandstone into which the schist gradually passes, the schistosity having been developed parallel with them. Under the microscope, it shows a thick felt of prisms and needles of pale greenish-white actinolite imbedded in a feldspathic base, the grains of which possess shadowy boundaries and hazy, uncertain extinc-

tions. The actinolite in this, and in one or two other cases, was not at first readily recognized as such, owing to the fact that when the needles are small and thin, and particularly when the section is cut in certain directions, they do not give the usual bright interference colors of hornblende, and it is difficult to determine their oblique extinction. The pleochroism in such cases is often very faint; and they might be mistaken for zoisite. The study of some inclusions in the serpentine, presently to be described, left, however, no doubt of their identity.

About two hundred feet farther east along the beach, the rock is plainly a sheared sandstone, with the ordinary gray color, and showing scales of secondary mica in the shear planes. Under the microscope it shows a typical sheared structure, with brilliantly polarizing wisps of muscovite lying in parallel lines. The original clastic structure is still present, but recrystallization has gone on, surrounding the remnants of the original grains by a fine mosaic of quartz and feldspar. Still farther away from the serpentine, the sandstone resumes its regular bedding, and shows no alteration beyond the appearance of having been subjected to unusual pressure, which characterizes it over the greater part of the island.

A closely similar schist to that just described is found on each side of the northern end of the dyke. That on the western side appears to take the place locally of the usual glaucophane schist. It is characterized macroscopically by abundant small glistening cubes of pyrite.

Some Peculiar Inclusions in the Serpentine.—At various points in the main mass of the serpentinized dyke, there occur inclusions, often of considerable size, and possessing a peculiar petrographic character. These were first noticed on the hill slope to the east of the barracks, as two isolated masses of rock, much harder and tougher than the serpentine, which have been quarried for road metal. The exact contact between the two rocks, although not always apparent at a casual glance, can in every case be determined with absolute precision as a clean-cut line of division, which shows that the masses are surrounded on all sides by serpentine, and have evidently once been covered by it also. Near the center of each mass the rock is a fresh gray color, heavy, even-grained, and exceed-

ingly tough. On freshly fractured surfaces the lens shows numerous cleavage faces of striated feldspar, and the rock would be tentatively classed in the field as a fairly fresh diabase. Near the margins the rock becomes finer grained, and at the contact is quite dense and cryptocrystalline in texture. This would ordinarily be taken as fair evidence of its intrusion into the serpentine; but the latter rock shows no perceptible alteration, and microscopic study of the inclusions seems to throw much doubt upon the intrusion hypothesis.

In thin section the rock shows a holocrystalline granular structure, being made up of large allotriomorphic plates of augite, in a groundmass of plagioclase. The augite is nearly colorless, with a slight brownish tinge, is not pleochroic, and resembles very closely the augite of the fourchite. The plates are frequently twinned, occasionally polysynthetically, and show the usual cleavages of monoclinic pyroxene. Many of the plates and grains are surrounded by a dark cloudy border, while others are fringed with hornblende, usually in the form of delicate needles of pale green actinolite. The most remarkable thing about the rock, however, is the feldspathic base in which the augites lie. This is made up of clear, perfectly fresh plagioclase, in grains of considerable size, and with no regular boundaries. The grains do not abut sharply and decisively against each other but shade off in a wavy, uncertain manner between crossed nicols. When twinning occurs it is usually in the form of broad bands, or the grain consists of two simple halves. Observations made upon a number of plates showing a symmetrical extinction on either side of the composition plane, in the great majority of cases afforded extinction angles of about 15°, or less, and the plagioclase is almost certainly albite. It is generally remarkably fresh and clear, but has a clouded appearance under very low powers, due to the presence of included needles of actinolite, which pierce it in all directions, and are identical in every respect with those already mentioned as fringing the augite. Under high powers the cross sections of the smaller needles are irregular in shape, but the larger ones give the characteristic rhombic forms of the amphibole group.

A slide from the rock in the upper of the two little quarries,

which is macroscopically identical with the preceding, differs in having the augite in rather smaller plates, which have been almost wholly transformed to hornblende. Only by careful search can here and there a remnant of the augite be found occupying the central portion of a crystal of hornblende. The feldspathic base is similar to that in the preceding rock, but even more thickly crowded with needles and prisms of actinolite. Not all of the hornblende of this slide is of the green variety, however. Many of the larger irregular areas, resulting from the conversion of the augite, are occupied by a strongly pleochroic brown variety, showing, in sections transverse to the prism, the usual amphibole cleavage. Assuming that the optical scheme is the same as for ordinary hornblende, then the pleochroism is $\mathfrak{a}$ = light dirty green, $\mathfrak{b}$ = deep chestnut brown, and $\mathfrak{c}$ = light yellowish green. One crystal was noted twinned in the ordinary manner, parallel with the orthopinacoid. There is no apparent regularity in the distribution of the brown variety, for the individuals are often mottled green and brown. The larger grains of hornblende, especially the brown, appear to be perfectly compact, and yet there can be little doubt that it is all secondary, and can be seen fringing off on the borders into needles of actinolite. Any doubt that might have existed as to the secondary origin of the clear feldspar, and its inclosed actinolite crystals, was wholly dissolved by the discovery, in a slide from another inclusion, of fine cracks traversing the slide, and filled with the same minerals as the matrix or groundmass of the rock. These are very apparent in ordinary light, owing to the greater clearness of their filling, but the distinction vanishes almost completely between crossed nicols.

Nearly all the slides show small areas of gray, cloudy material, occasionally surrounding a dark opaque grain. These are evidently leucoxene, resulting from the decomposition of ilmenite. Small patches of pyrite are also not uncommon.

A slide cut from a specimen taken about two feet from the contact with the serpentine, deserves notice for the exceptional opportunity it affords of studying the development of the actinolite needles. The large grains of augite are generally surrounded by a border of brown, cloudy material, of no great width; then follows

a zone of brown or green hornblende, which in turn has its outer edge fringed with a bristling array of the sharp, slender actinolite needles, which penetrate into the surrounding feldspar. Similar needles are scattered profusely all through the clear plagioclase, either singly or in parallel aggregates with bristling ends.

Other outcrops present macroscopic variations from the rocks just described, but the micro-structure is in all cases similar, or presents but trifling differences. Close to the road, as it crosses the saddle going northward from the barracks, a mass of decomposed rock, weathering like the ordinary fourchite of Point Stuart, is imbedded in the serpentine, and traversed by one or two narrow veins of a mineral which appeared in the field to be serpentine, but which was subsequently determined to be an aggregate of zoisite. As nearly as can be made out under the microscope, it is merely a decomposed facies of the rock just described.

Another inclusion is in the wedge-shaped southern end of the large northern division of the dyke. Portions of this outcrop exhibit a more or less foliated structure, are brittle and resonant when struck, and present the glittering fracture of many fine-grained diorites; but the microscope shows that they are merely facies of the rock forming the inclusion first described, the augite having wholly disappeared, and the resulting hornblende being mostly of the brown variety. The groundmass in the two cases is identical.

In the ravine which separates the main northern division of the dyke from the southern part, and just south of the preceding outcrop, the relations of the various rocks are obscure. A little knoll, almost in the line of the dyke, is occupied mainly by a rock of similar character to that described as forming masses in the serpentine, consisting mainly of hornblende and clear, secondary plagioclase, the latter being thickly crowded with needles of actinolite. Closely associated with this rock is the San Francisco sandstone, fragments of which showing various degrees of alteration occur scattered over its surface, although the actual exposures of the rock *in situ* are extremely poor. Many of these fragments have a darkened and baked appearance, and when one piece with a particularly cindery aspect was examined microscopically, it was found to retain the original clastic structure of sandstone; but between the grains

were areas of dark, interstitial material, full of gas-filled vesicles, and perfectly isotropic. It is undoubtedly a vesicular glass, formed by the fusion, and subsequent quick cooling, of the finer interstitial portions, and possibly more basic constituents, of the sandstone. It is fairly certain that such a glass could only result from the comparatively rapid chilling of the fused material, and this affords new evidence in support of the hypothesis that the original top of the serpentine dyke has here not yet been exposed by erosion.

The small area of altered eruptive rock is mapped as if it were surrounded by sandstone, in which case it is the only mass of such rock found outside of the serpentine area. Its altered condition, however, can be consistently explained only by the supposition that the serpentine is not far away, and, owing to the manner in which the relations of the rocks are concealed at this spot, it may be much closer than is indicated by the mapping.

The origin of these inclusions has proved a very puzzling question. From the fact that they can frequently be observed to become finer grained as the contact with the serpentine is approached, it might be argued that they are intrusive into the latter rock. On the other hand, these isolated masses have been considerably metamorphosed, while the adjacent serpentine shows no signs of alteration, nor of penetration by apophyses. Lastly the distances between these masses, and their complete isolation from each other, preclude the idea suggested in explanation of somewhat similar occurrences,* that they were once a dyke in the serpentine, which has been disrupted, and the parts displaced by shearing. On the other hand, it is very improbable that these numerous separate bosses of igneous rock should have been intruded with such persistency into the relatively massive and resistant serpentine, and yet have avoided so completely the shattered and upturned strata on either side. The only known occurrence of this rock outside of the serpentine area is in the small ravine previously noted, and where it is quite probable that the serpentine is just below the surface.

The hypothesis most in harmony with the observed facts is that the masses of rock at present included in the serpentine, at one time occupied a more or less continuous fissure, as a dyke of much

*Geology of Tehama, Colusa, Lake, and Napa Counties, by H. W. Fairbanks, 11th Rept. State Mineralogist (California), p. 70.

smaller size than the serpentine, or, possibly, as a series of plugs, filling vents situated upon a line of disturbance. It is considered probable that from this fissure, or from these vents, came a portion of the fourchite magma, although it is admitted that the only direct evidence for such a view is the identity in character of the augite in the included masses and in the fourchite. After this first intrusion had taken place, and the fourchite had solidified, it is supposed that the intrusion of the rock from which the serpentine has been derived, followed, forcing aside the walls of the fissure, so as to give it a much greater width than before, and catching up and including within its mass the fragments of the earlier dyke.

The fact that the rock from which the serpentine was formed was probably made up largely of diallage, while the fourchite is highly augitic, points to a possible genetic relation between the two rocks, suggesting that the rock at present represented by the serpentine was the final basic residuum erupted from the reservoir that had previously furnished the fourchite. Through the lack of substantial evidence as to the relative age of the two rocks, this can be taken as little more than a suggestion.

CHEMICAL ANALYSES.

The following analyses were made by the writer in the mineralogical laboratory of the University of California, upon specimens representative of typical facies of the rocks whose petrographical characters have been described in the preceding pages.

	I.	II.	III.	IV.
SiO_2	46.98	42.06	80.21	70.50
Al_2O_3	17.07	2.72	7.99	
Fe_2O_3	1.85		included with FeO	
FeO	7.02	2.88	3.35	
CaO	12.15	....	1.10	
MgO	8.29	39.53	1.54	
K_2O	.53	not estimated	.22	
Na_2O	2.54	" "	5.97	
P_2O_5	.09	....	....	
Loss on ignition (H_2O)	4.86	12.04	.74	
	101.38	99.23	101.12	
Sp. gr.	3.20	2.61		

I. Fourchite of main sill, same facies as shown in Pl. 13, Fig. 1.
II. Serpentine, hard sound nodule in crushed matrix.
III. Contact-metamorphic schist next to serpentine.
IV. Silica determination of sandstone from Quarry Point.

CONCLUSION.

The most important general result that has been arrived at from a study of the rocks of Angel Island, is the establishing of the fact that holocrystalline glaucophane (blue amphibole) schists can be formed by the contact metamorphism of the San Francisco sandstone and associated cherts through the intrusion of certain basic igneous rocks. It follows from the foregoing statement, that the attempt to assign all of the glaucophane schists of the Coast Ranges to a general regional metamorphism, or to a simultaneous metamorphism of any kind, must be abandoned. Direct evidence of the non-contemporaneity of at least two rocks characterized by the presence of blue amphibole was afforded by the occurrence, in the unaltered San Francisco sandstone, of abundant pebbles of a peculiar rock not known *in situ*, bearing well-developed needles of the mineral, while the same sandstone has itself been metamorphosed into a perfect glaucophane schist, at the contacts with the fourchite and serpentine. In the light of these facts, the remarkable and often perplexing manner in which various varieties of crystalline schist are associated with areas of serpentine about San Francisco Bay, becomes susceptible of explanation. It is believed that in many such occurrences the accompanying schist can be shown to be the direct result of local contact metamorphism.

It is also believed that the finding of radiolarian remains abundantly present in the cherts of Angel Island, and in those of other localities, is an important step toward an understanding of the true nature of these interesting rocks. It shows that a certain correspondence exists between them and the radiolarian cherts of other portions of the globe, and is an addition to the mass of evidence that is gradually accumulating to controvert the view that they represent ordinary shales silicified during regional metamorphism.

In regard to the serpentine, it is now scarcely necessary to emphasize the fact that, like the serpentine of the Potrero, and,indeed,

like all the large masses of serpentine with which the writer is familiar in the vicinity of San Francisco Bay, it has resulted from the serpentinization of a holocrystalline basic eruptive rock, and is in no sense a metamorphosed sediment. In the case of Angel Island this original rock appears to have been of rather an exceptional character, consisting mainly of diallage. No indications of the former presence of olivine have been detected, nor has entirely satisfactory evidence of rhombic pyroxene been obtained. Although the two last-named minerals are preëminently those most likely to form serpentine, yet the serpentinization of diallage is by no means unknown. Turner* mentions a dyke in which "the pyroxene is plainly altering to serpentine," the context indicating that the pyroxene is monoclinic.

As to the fourchite, little remains to be said, save, perhaps, that it affords in its various facies an example of magmatic differentiation similar to many that have been described of late years, although the occurrence is not sufficiently favorable to throw much light upon the general law according to which the differentiation has taken place.

It may also be well to lay a parting emphasis upon the statement that the fourchite, together with the eruptive rocks of Point Bonita described in a preceding paper, are identical with, or are included in, various rocks of eruptive character described by earlier writers as metamorphosed sediments, and to which Becker has given the names of pseudo-diabase, pseudo-diorite, etc.

In conclusion, the writer desires to express a grateful sense of obligation to Professor Lawson, who has always proved an unfailing source of aid and encouragement. Acknowledgments are also due to Lieutenant L. P. Brant, Post Adjutant, and to Dr. C. T. Peckham, of the U. S. Marine Hospital Service, for courtesies of which the author was the recipient while at work upon the island.

Geological Laboratory,

University of California, October 8, 1894.

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*Geological Notes on the Sierra Nevada, Am. Geologist, Vol. XIII, 1894, p. 299.

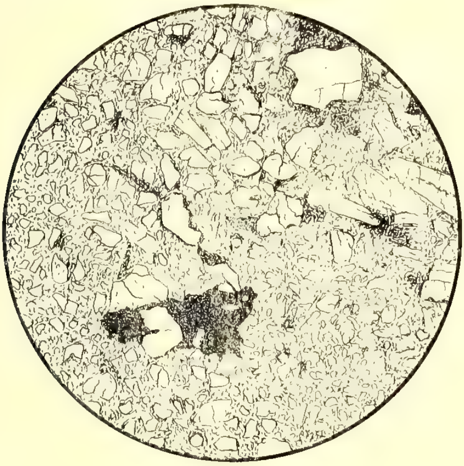
EXPLANATION OF PLATE 13.

FIGURE 1.—Fourchite from the main sill, showing granulitic character of the augite. The prisms of zoisite, and the filmy areas of blue amphibole, cannot be delineated, apart from the general ground mass, in a drawing of this degree of magnification. The dark patch is an aggregate of pyrite. × 40.

FIGURE 2.—Spheroidal facies of fourchite (spheroidal basalt) at Point Blunt, with skeleton crystals of plagioclase. The longer, lighter colored brushes are composed of plagioclase microlites, while the shorter and darker bunches are probably augite. The greater part of the slide is occupied by a gray cloudy glass. One porphyritic crystal of plagioclase is shown that has been broken in the magma, and also contains an embayment filled with the glassy base. × 40.

FIGURE 3.—Altered radiolarian chert from near the contact with the serpentine dyke, showing the characteristic mode of development of the glaucophane in long, hair-like crystals, during an incipient stage of the metamorphism. Although this particular slide is from the serpentine contact zone, it might just as well represent identical facies found alongside the fourchite. It is impossible in a drawing to give any adequate idea of the beauty and delicacy of these sheaves of blue capillary crystals lying in a matrix of clear quartz grains that are dusted with minute garnets and other crystal grains. × 40.

FIGURE 4.—Section of the typical glaucophane schist, from the contact zone west of the serpentine dyke, cut at right angles to the direction of schistosity. The cross sections of the amphibole show the frequent zonal structure, while the occasional longitudinal sections exhibit the transverse parting and displacement referred to in the text. × 40.



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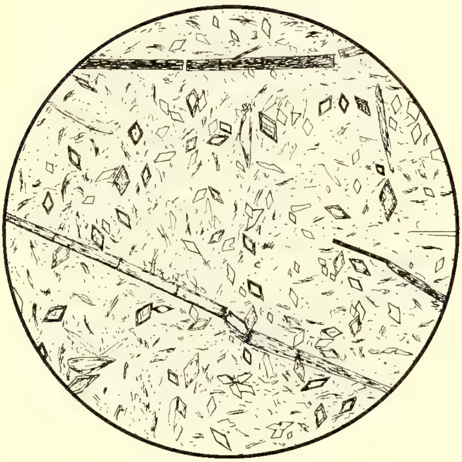

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APPENDIX.

NOTE ON THE RADIOLARIAN CHERT FROM ANGEL ISLAND,

AND FROM

BURI-BURI RIDGE, SAN MATEO COUNTY, CALIFORNIA.*

BY

GEORGE JENNINGS HINDE, PH. D.

BOTH the red, jaspery rock from Angel Island and the light colored rock from the Buri-buri Ridge are crowded with radiolaria, and, though in external appearance these rocks differ considerably from each other, the character and mineral condition of the organisms of which they are mainly composed are similar in both. In the red rock from Angel Island no traces of the minute radiolaria can be distinguished, even with a strong simple lens, on freshly fractured surfaces, but where a very thin section of the rock is examined, these organisms appear in transmitted light as small, clear, transparent dots, mostly with rounded contours, thickly imbedded in the red matrix. Under the microscope these transparent bodies are seen to be without any definite walls of their own, and for the most part without any traces of structure, and their outlines are only marked, in what appear under high powers as indistinct and indefinite boundaries of the reddish matrix. As a rule, these bodies show only the solid infilled casts of the originally hollow organism; the latticed walls surrounding the hollow, have apparently been indistinguishably merged into the clear microcrystalline silica of which the cast is composed, and thus there is now left only an ill-defined contour of the original form from which to determine its character

*Radiolarian remains having been discovered in the cherts of the San Francisco peninsula by Professor Lawson and in the cherts of Angel Island by the writer about the same time, chips and slides of the rock from both localities were forwarded by Professor Lawson to Dr. G. J. Hinde, of London, England, the well-known authority in this line of research. Dr. Hinde very kindly furnished the present note concerning these interesting fossils.

and relationship. In a few instances the original hollow has been in part filled with the stained matrix, so that the thickness of the bounding walls is shown, and this is more particularly the case with the conical forms of the genus *Dictyomitra* (Pl. 14, Figs. 15, 16, 17) in which the basal portion was open. In the spined forms the spines appear as projecting transparent rays extending from the clear central mass. Rarely indeed are traces of the characteristic lattice structure of the radiolarian test preserved, but occasionally it is shown by the rounded dots of the red matrix on the surface of the cast, in which also the original regular arrangement of the holes in the test can be recognized (Fig. 7).

In the light-colored Buri-buri rock there is but little difference in the appearance of the silica filling the radiolarian casts and that of the matrix, consequently they can only be faintly distinguished in thin sections, but usually the silica of the cast is free from the minute granular particles which abound in that of the matrix. Frequently, however, in this rock the radiolaria have been infilled with a light brownish silica, which allows the wall of the test to be distinguished, but the details of the structure have been obliterated just as much in this light-tinted rock as in the red rock from Angel Island.

The unfavorable state of preservation of these radiolaria makes a specific determination almost out of the question, and even the genera to which they belong cannot, as regards most of them, be positively recognized. The majority of them evidently belong to simple spheroidal and ellipsoidal forms, included in Hæckel's suborders Sphæroidea and Prunoidea, and they range in size from .055 to .3 mm. in diameter. The spherical forms may be included in the genus *Cenosphæra*, Ehrenberg (Figs. 1, 2 and 3), and *Carposphæra*, Hæckel; in this latter there is an inner medullary shell (Fig. 4). The ellipsoidal forms with smooth contours (Figs. 5, 6, 7) probably belong to *Cenellipsis*, Hæckel; they are very abundant; those forms, with numerous radial spines on the surface (Figs. 8, 9), come into the genus *Ellipsidium*, Hæckel; and those with a single extended spine or ray at one pole (Figs. 10, 11) into *Lithapium*, Hæckel. There are further some peculiar types which may provisionally be placed in the suborder, Discordea, Hæckel. In one

the central test is somewhat triangular in outline, with three large spines (Figs. 12, 13), resembling a Jurassic species named by Dr. Rüst, *Tripocyclia trigonum.* In another, the central portion of the test is subquadrate, and from it four broad arms extend diagonally (Fig. 14). This has a general resemblance to some fossil forms of *Hagiastrum*, Hæckel. The suborder Cyrtoidea, Hæckel, is numerously represented, and the conical turreted examples of the genus *Dictyomitra*, Zittel (Figs. 15, 16, 17), are the best preserved and most characteristic radiolaria occurring in these rocks. There are also a few forms of the allied genera *Lithocampe*, Ehrenberg, and *Sethocapsa*, Hæckel (Figs. 18, 19). It is fairly certain that examples of many other genera besides those mentioned are present in the rocks, but they are too indistinct to allow of identification, and the only chance of obtaining further knowledge of these, rests on the discovery of nodules or other portions of the beds in which the organisms are better preserved.

The forms which can be thus imperfectly identified are too few to permit of any satisfactory comparison with the fossil radiolaria from other localities. The character of the rock and the mode of preservation appear to be very similar to what is met with in the red radiolarian jaspers and cherts of Jurassic and Cretaceous age, which have been described by Dr. Rüst* from the Tyrol, Switzerland, Hungary and other places. Thus, for instance, in the upper Jurassic or Tithon beds of Allgäu in the Tyrol, there are red jaspers, filled, like these Angel Island red cherty rocks, with radiolaria, so that Rüst compares them with the radiolarian mud brought up from the greatest ocean depths by the *Challenger.* Very similar red rocks have also been described by Pantanelli in Tuscany,† and by Dr. C. P. Parona‡ from Cesana, but the geological age of these rocks is not yet established. There is a very considerable resemblance in the Cesana rock, as also in the mode of preservation, and the general character of the radiolaria in it, with the Californian Angel Island material. The radiolaria from Cesana were considered

*Palæontographica, Bd. XXXI, 1885, Bd. XXXIV, 1888.

†I. Diaspri della Toscana e i loro fossili. Accad. d. Lincei. Mem. 1880.

‡Sugli Schisti Silicei a Radiolarie di Cesana. R. Accad. Scienze di Torino, XXVII, 1892.

by Rüst to indicate a horizon of the lower Gault, but Dr. Parona thinks that the beds are much older.

The most distinctive feature in the Californian radiolaria is the number and variety of forms of the genus *Dictyomitra* present in it, and it is not without significance that this genus is also abundantly represented in the Jurassic and Cretaceous radiolarian jaspers and cherts mentioned above.

No other microscopic organisms besides radiolaria can be seen in the Angel Island or in the Buri-buri beds. It is quite possible that diatoms may have been intermingled with radiolaria in these deposits, but the fossilization, which has been sufficient to obliterate most of the radiolarian structure, would completely destroy all traces of the smaller and more delicate diatoms.

Below are some further details respecting the forms which permitted of partial identification.

RADIOLARIA.

Suborder, SPHÆROIDEA, Hæckel.

Genus, **Cenosphæra,** Ehrenberg.

To this genus belong the forms with circular or subcircular outlines, without spines. (Figs. 1, 2, 3.) There is considerable variation in the size of different examples; they range from .055 mm. to .3 mm. in diameter. The lattice structure is in almost all cases destroyed; in one instance, however, the holes in the test are shown in section. (Fig. 1.) These apparently spherical forms occur both at Angel Island and Buri-buri Ridge; they are more common in the latter bed.

Genus, **Carposphæra,** Hæckel.

Only a single example with an inner medullary shell has been noticed. (Fig. 4.) The diameter of the test, .125 mm.; of the inner shell, .045 mm. From Buri-buri Ridge.

Suborder, PRUNOIDEA, Hæckel.

Genus, **Cenellipsis,** Hæckel.

The tests are regularly oval in outline, with smooth surfaces. (Figs. 5, 6, 7.) Their long diameters range from .1 to .22 mm., the shorter from .08 to .185 mm. In one specimen (Fig. 5) the thickness of the wall is .015 mm., but no perforations are shown;

in another (Fig. 7) some of the holes in the test are shown by sub-circular spots .025 mm. in width. These oval forms are common both at Angel Island and the Buri-buri Ridge.

Genus, **Ellipsidium,** Hæckel.

The tests are elliptical in outline, with numerous radial spines. (Figs. 8, 9.) In one form (Fig. 8) the long diameter is .12 mm., the wall .01 mm. in thickness, and the spines somewhat less in length. In another (Fig. 9), the greater diameter is .27 mm. and the spines .03 mm. in length. There are traces of the holes of the test in this form. From Angel Island.

Genus, **Lithapium,** Hæckel.

The tests are oval in outline, at one pole a stout radial spine. (Figs. 10, 11.) In one example (Fig. 10) the total length including spine is .4 mm., length of spine .21 mm., breadth of test .14 mm. In a smaller form (Fig. 11), with an incomplete spine, the long diameter is .11 mm., and the shorter .085 mm. From Angel Island.

Suborder, DISCOIDEA, Hæckel.

Genus, **Tripocyclia,** Rüst.

The test is roughly triangular in outline; the sides are straight or slightly curved; from each angle a long, straight or partly curved spine extends. (Figs. 12, 13.) The diameter of the test is .15 mm.; the spines range from .18 to .33 mm. in length. In general outline this form resembles the Jurassic *Tripocyclia trigonum*, Rüst,* which has been also recorded by Dr. Parona from the Italian Jurassic of Laveno and also in the Cesana schists. This form is not uncommon at Angel Island, but it is seldom shown in the sections with the spines complete.

Genus, **Hagiastrum,** Hæckel.

Central portion of test subquadrate in outline; from each corner there is a long, stout arm extending diagonally. (Fig. 14.) The arms are apparently incomplete. No structure preserved beyond traces of holes in one of the arms. Diameter of test .1 mm., length of arms .2 mm. I have only seen a single specimen of this form, which differs from the existing examples of the genus in the diagonal direction of the arms. Dr. Parona† has, however, referred a

*Palæontographica, Bd. XXXI, 1885, p. 293, Pl. XXX, Fig. 3.

†Atti. R. Accad. Scienze Torino, vol. XXVII, p. 15 (sep. copy), Pl. Fig. 31.

form apparently similar in this respect to *Hagiastrum.* From Angel Island.

Suborder, Cyrtoidea, Hæckel.

Genus, **Dictyomitra,** Zittel.

Sp. *a* (Fig. 15). Test elongated, conical, summit acute; gradually and evenly increasing in width to the base. There are five or six transverse partitions or constrictions. No perforations shown. Length .27 to .301 mm., width at base from .1 to .13 mm. This is not an uncommon form; it occurs both at Angel Island and Buri-buri Ridge.

Sp. *b* (Fig. 16). Test conical, summit obtuse, gradually increasing in width to the base. There are nine or ten nearly straight transverse partitions, about an equal distance (.025 mm.) apart. Length .26 mm., width at base .14 mm. Rare. Buri-buri Ridge.

Sp. *c* (Fig. 17). Test elongate conical, summit obtuse, very gradually increasing in width to the base. There are about five projecting ridges, which represent as many constrictions or segments. Length .2 mm., width at base .08 mm. Not uncommon. Angel Island.

Genus, **Lithocampe,** Ehrenberg.

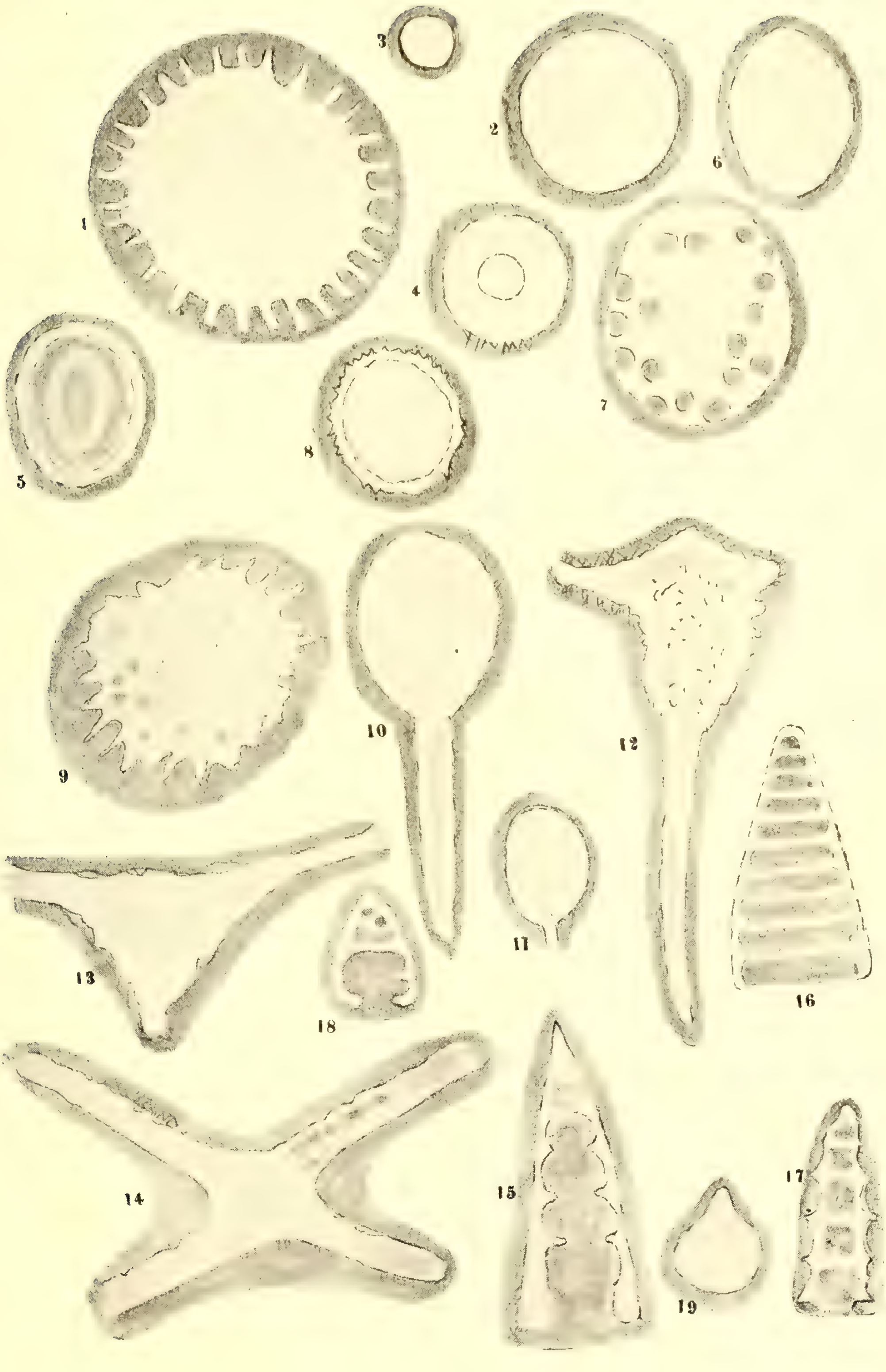
Test subconical, summit obtuse (Fig. 18); in the upper portion there are two or three small partitions and two larger below. The aperture constricted. Length .085 mm., width a short distance above the base .08 mm. Rare. Buri-buri Ridge.

Genus, **Sethocapsa,** Hæckel.

Flask or pear shaped, surface smooth, no perforations shown. (Fig. 19.) Length .21 mm., greatest breadth .135 mm. Angel Island. Rare.

EXPLANATION OF PLATE 14.

Note.—The heavier shading on the outside of the figures is intended to represent the rock matrix in which the forms are imbedded. Scale, nat. × 200.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THE GEOMORPHOGENY* OF THE COAST OF NORTHERN CALIFORNIA.

BY

ANDREW C. LAWSON.

CONTENTS.

INTRODUCTION.

In the month of June last the writer made an excursion on horseback along the coast of northern California from the Golden Gate to Eureka. The trip was taken primarily for recreation, but also with the design of extending the reconnaissance which the

*The origin, or process of development, of the *geomorphy* of any portion of the earth's crust, *geomorphy* being a synonym of *topography* in the broader application of that term.

writer had the previous year made of the coast south of San Francisco with reference to its post-Pliocene diastrophism.* It is the purpose of this paper to record the observations made during the trip, and to present certain inferences from them. The observations are few and are deficient in detail; but when supplemented by the information afforded by the Coast Survey charts and by the application of certain well-known principles of geomorphogeny, they will be found sufficient, it is believed, to warrant the general hypothesis arrived at. Briefly, this states that the present geomorphy is the result of the following sequence of events:—

1. The development in Pliocene time of a great coastal peneplain, with correlative accumulation of marine sediments.

2. The orogenic deformation of parts of this peneplain and the folding of the Pliocene strata, the general altitude of the peneplain, where not so disturbed, remaining about the same.

3. The reduction of the upturned soft Pliocene strata to base level, and the limited extension of the peneplain in between the uplifted blocks of the other disturbed areas.

4. The progressive uplift of this peneplain, with its residual monadnocks, to an elevation for the plain of from 1,600 to 2,100 feet above the sea level, the adjacent mountainous tracts participating in the same movement.

5. The advance in the new geomorphic cycle to a stage of late adolescence or early maturity.

6. A very recent local sag or depression of about 100 miles of the coast adjacent to the Golden Gate, and the consequent flooding of the stream valleys by the ocean.

EVIDENCES OF GENERAL UPLIFT.

Traces of an Ancient Peneplain.—The Coast Ranges of northern California comprise, besides the mountains proper, which, except for isolated peaks, are distant from the ocean, a broad coastal tract which may be said to be devoid of true mountain topography. This tract is clearly a dissected plateau, and impresses itself as such upon the observer very forcibly when viewed from any point not lower than its general level. The plateau is now represented only

*This Bulletin, Vol. 1, No. 4.

by long, roughly level-topped ridges, which are separated from one another by long, narrow valleys. At the heads of the streams which drain the valleys the ridges are frequently confluent. The ridges have a remarkable constancy of general altitude. The observer stationed on one which is slightly more commanding than the rest, beholds a vast expanse of country with no prominent profile against the sky, throughout the tract, in Sonoma and Mendocino Counties. Ridge succeeds ridge in seemingly endless sequence, and, if one overlooks the foreground, the general effect of the ridges falling away in perspective is that of a plain. So stationed he can easily imagine the intervening valleys filled flush with the crests, and realize how aptly Cook's description of the New Jersey highlands, quoted by Davis and Wood,* applies to this portion of California, although the features here are on a larger scale. The plain so restored would be neither level nor even. It would be a sloping plateau of low relief. Along the front of this plateau where it overlooks the ocean its general altitude is about 1,600 feet. Back from the coast where it passes into the higher and more mountainous tract of central and eastern Mendocino County it has an elevation of about 2,100 feet. On entering Humboldt County several sharp peaks rise abruptly above the general level of the dissected plateau to altitudes of from 3,000 feet to 4,000 feet; but remnants of plateaux clearly encircle these and give their middle slopes a distinctly terraced aspect. It is evident that, northward of the 40th parallel of latitude, the forces which effected the evolution of the original plain had made but little headway as compared with the coastal region to the south of the same line, or they had been interrupted in their work by orogenic disturbances. The plain in Humboldt County presents no broad expanse, as in Mendocino and Sonoma Counties, but may be followed in between an open cluster of mountain peaks and ridges. The present reconnaissance establishes the fact of its extension as far as the Bear River Ridge. It doubtless extends up the coast, however, far beyond the limit set to the exploration.

That this great dissected plateau represents an ancient peneplain,

*Geographic Development of Northern New Jersey, Proc. Bost. Soc. Nat. Hist., Vol. XXIV, 1889.

which has been uplifted from a nearly baseleveled condition to its present altitude, seems beyond question. The rocks of which it is composed are of various ages, of various degrees of hardness, and have been throughout the region so disturbed that their original horizontal condition is practically nowhere to be found. The surface of the ancient peneplain consists of the beveled edges of the upturned strata. On the summit of one of the characteristic ridges of the plateau between Usal and Kenny, numerous water-worn pebbles were found at an elevation of about 1,600 feet, which can only be interpreted as remnants of the stream gravels of the ancient peneplain.

Former Baselevel Bench Marks.—The uplift of this coastal peneplain inaugurated a new cycle of geomorphic evolution. A new block was given to the great sculptor Erosion, and he immediately began to shape it. The ancient impotent streams were revivified, and proceeded to sink trenches across the plain. The forces of the ocean strand, tireless in their activity, now became effective for corrasion, and cut broad terraces in the seaward face of the rising block. The extent to which this river trenching and oceanic terracing have proceeded, as well as the state of preservation of the terraces and their sea-cliffs, afford a measure, indefinite and relative though it be, of the time since the uplift began.

In the wave-cut terraces, also, we see that the uplift proceeded by stages. It might be presumed that these stages would also be represented by stream terraces in the valleys. This, however, is true only to a limited extent and chiefly for the earlier and middle stages of the uplift. From the prevailing absence of important stream terraces in the lower or newer portions of the valleys, the inference seems to be warranted that the stages or stoppages in the upward movement were not of long duration, and that there was not sufficient time for the streams to corrade broad flood-plains. The corrasion of the shore forces is much more vigorous, persistent, and uniform than that of streams, hence the time that sufficed for the sculpture of an ocean terrace was often insufficient to permit of the formation of a corresponding flood-plain. In the marine terraces, therefore, we find more abundant bench marks of the former baselevels of the coast. The stream terraces when found are, how-

ever, fully as significant as the marine, and are perhaps more important in that they indicate an exceptionally long-continued stoppage in the general upward movement. We may now proceed to indicate in the briefest possible terms the occurrence of these baselevel bench marks, both marine and fluviatile, along the coast between the Golden Gate and Eureka.

Between the Golden Gate and the mouth of the Russian River the most prominent of the former strand lines of the coast are the wave-cut terraces of Duxbury Point and Point Reyes. The former is a very distinct plateau-like bench, which has been cut into the southern end and eastern side of the ridge which separates Ballenas Bay from the open ocean. Its elevation is from 220 to 230 feet, according to the Coast Survey contours. The terrace at Point Reyes is broader, and, owing to subsequent degradation, somewhat vaguer than that of Duxbury Point when viewed at close quarters. Its greater breadth may be ascribed partly to the more projecting, and therefore more exposed, position of the point, and partly to the fact that it has been cut into a terrane of soft Miocene shale (Monterey Series) which occupies that portion of the point to the north of the bold ridge of granite and conglomerate upon which the lighthouse is situated. Its partial degradation is due to the imperfect terracing action of later stages of uplift, and to the fact that it is traversed by the drainage of the high ridge to the east of it. This terrace is sparingly strewn with shore-worn pebbles. The elevation of the terrace is about 300 to 330 feet. On Point Reyes there are other lower terraces, but topographically they are quite subordinate to the broad dominant terrace here referred to. On the ocean side of the main coast ridges, which lie to the east of Ballenas and Tomales Bays, there are numerous suggestions of higher terraces, but they are nearly all vague in their profiles and in their horizontal extension. They seem to have suffered severely from degradation, and they occur on a terrane which, in the writer's experience, wherever it occurs along the Californian coast, is little adapted to the preservation of such forms.

A little north of the mouth of the Russian River well characterized oceanic terraces, at various high altitudes above the present strand, form prominent features of the coastal topography. The

series of these abandoned strands is most complete and most conspicuous in the vicinity of Fort Ross, the former seat of the Russian occupation of northern California. At this point the edge of the coastal plateau breaks away in great steps, which have the characters of wave-cut terraces. That these features are better developed at this point than is the case for portions of the coast farther south, is probably due to the fact that just where the terraces become most pronounced we enter upon a geological terrane which is lacking farther south, viz., the strata which have been called the Wallala formation; and these rocks appear to be better adapted both for the sculpture of terraces and for their preservation, owing to the greater homogeneity of the rocks. With the aid of a contour map of this portion of the coast, executed by the Coast and Geodetic Survey, on a scale of 1:10,000, which was kindly placed at the writer's disposal by Mr. G. W. Call, of Fort Ross, he was able to determine approximately the altitude of the more prominent of these terraces, their character being well expressed on the map. The highest terrace is at a distance of two and one-half miles from the fort, and is traversed by the wagon road along the upper part of the ridge, overlooking the sea, just before its enters upon the steep grade to the fort. The altitude of the terrace is 1,520 feet above sea level. Its characters as an ocean strand are undoubted. Sea-cliff, sloping terrace, and boulder beach in the lea of the cliff are all well preserved. Evidences of shore action at higher altitudes have not been observed. The coastal plateau here is represented by a fairly level-topped ridge a little over 1,600 feet high; and it is possible that higher strands may have existed and been obliterated, or may yet remain and have escaped observation. The proximity of this terrace, however, to the summit of the dissected plateau affords a presumption that it is the highest oceanic strand which we are likely to find.

The more prominent wave-cut terraces below this highest one are situated at 1,400, 1,180, 760, 440, 350, and 280 feet respectively above sea level. There are many other less prominent terraces, which, though quite apparent to the eye, are but vaguely expressed in contours even on this scale, so that they could not be identified on the map with certainty and their elevations determined. Sand and

gravel beaches also occur in the embayments at high altitudes. A fine beach of this kind is well exposed at the schoolhouse on the road between Sea View and Plantation, a few miles north of Fort Ross. The lower wave-cut terraces, in the vicinity of Fort Ross, are very broad, and are among the particularly fine examples of this type of topography, for which the coast of California is remarkable.

From Fort Ross northward the lower terraces are finely displayed in practical continuity throughout Sonoma and Mendocino Counties, and along the coast of Humboldt County as far as it was followed, *i. e.*, to the mouth of the Eel River, but both in Humboldt and in the extreme northern portion of Mendocino, the sea-cliffs of the present strand are in such vigorous recession that the terraces have been in places undermined and obliterated.

It is not deemed necessary for the purpose of this paper to give detailed descriptions of these lower terraces which score the edge of the coastal plateau. Were there any doubt of their character, it would perhaps be desirable to enter into details. If, however, the judgment of the writer may be taken, it will be sufficient to say that they are wave-cut terraces of the most unequivocal kind, presenting in full all the characters of such forms, viz., the seaward slope, the planing off of the upturned strata, the residual stacks, the beach boulders, and the constant sea-cliff with its horizontal intersection of the plain of the terrace. Among the broadest and most sharply defined of these lower terraces are those in the vicinity of Point Arena, particularly the one upon which the upper part of the town of that name is built. Its exceptionally perfect and clear-cut profile is due to the fact that it has been carved out of the soft Miocene shale (Monterey Series), which here occupies the coast. The terraces here are quite similar to those which have been carved out of the same formation at Santa Cruz and San Pedro Hill, on the southern coast; and the repeated association of remarkably fine, broad, sharply cut terraces with the occurrence of this formation on the coast, seems to indicate that the latter is particularly well adapted for the sculpture of such forms, and for their subsequent preservation. This broad terrace at Point Arena has recently been ascribed by Mr. George Davidson, of the U. S. Coast and Geodetic Survey, to ice action. He says: "Point Arena is considered one of the most beautiful

examples of coast terraces or plateaus sculptured by the action of ice. The stratification is almost perpendicular. . . . The surface of the rock seems to have been absolutely planed off, and the different degrees of hardness of the layers in stratification had no apparent influence upon the mechanical forces at work."* This hypothesis of ice action is, as the writer has elsewhere shown,† untenable and entirely unnecessary as an explanation of the origin of the forms. They are simple cases of wave-cut terraces.

While the lower terraces may thus be followed practically for the entire extent of the coast, and critically examined at close quarters, the higher terraces, for a considerable part of the route followed by the writer, escape observation, or are only seen in the distance. This is largely due to the following facts: (1) The edge of the coastal plateau is not equally precipitous, and the high ground upon which the upper terraces may be scored is often distant from the shore road. (2) Even where the ascent from the shore to the summit of the plateau is abrupt, the upper portions of the slope are frequently timbered, and, so, much more obscure than the lower portions. (3) The higher terraces being much older have suffered more from degrading forces, and so appeal less strongly to the eye. In many cases they have doubtless been entirely obliterated. These causes conspire to make the evidence of the measure of the uplift, in so far as it depends upon marine terraces, defective for the portion of the coast between Greenwood and Ten-mile Creek. Elsewhere along the coast of Sonoma and Mendocino Counties terraces may be very commonly observed at altitudes which were estimated at various values from 500 to 1,000 feet. No marine terraces of higher elevation were observed; but as the writer disclaims having made any especial effort to find terraces at high altitudes, his inability to record them counts for little.

In the extreme northern portion of Mendocino County, at a wind gap overlooking the ocean, about eight miles north of Kenny, water-worn pebbles, well rounded, were observed on a terrace-like bench at an altitude which was estimated to be 1,200 feet above the

*Pacific Coast Pilot, 4th ed. U. S. Coast and Geodetic Survey, Washington, 1889, p. 272.

†This Bulletin, Vol. 1, No. 4.

sea. The cliff at the rear faces away from the ocean, and the bench is very probably the remnant of a stream terrace.

On entering Humboldt County conditions become more favorable for observation of the higher baselevel bench marks. Although there are several peaks and ridges rising to elevations of from 3,000 to 4,000 feet, plateau and terrace effects are common features of the topography at various altitudes from 2,100 feet downwards. The terraces on the flanks of the peaks eastward and southeastward of Point Delgada are particularly conspicuous at altitudes of about 1,500 feet or more. Farther north near Pennoyer's ranch there is a plateau tract at an altitude of about 2,100 feet which can scarcely be interpreted otherwise than as a portion of an ancient baseleveled plain.

In the valley of the Mattole River, near Petrolia, there are very clear and unmistakable remnants of ancient flood-plains terracing the valley at altitudes of from 500 to 700 feet. Far above this there are, on either side of the valley, plateau-like ridges at elevations which are probably not far from 2,000 feet. Above these rise peaks whose slopes are in sharp contrast with the plateau. Mount Blank, a few miles southeast of Cape Mendocino, appears on the Coast Survey chart as a plateau having a general elevation of 2,100 feet, with a few knobs rising to 2,200 feet. The most pronounced and persistent baselevel bench mark of this part of the Humboldt County coast is one which appears very constantly at between 900 and 1,000 feet. This is well displayed near Point Gorda as a wave-cut terrace, dissected by the Four-mile Creek. A corresponding terrace appears at the same altitude on the north side of the mouth of the Mattole, and remnants of it are seen all the way to Cape Mendocino. It is a striking feature of the seaward flanks of Mount Blank. On the crest of the ridge which terminates in Cape Mendocino, the coast road passes over the remnant of a gravel flood-plain at an altitude of about 950 feet, and west of the road there are terraces to an altitude of about 100 feet above the plain. Bear River is the modern representative of the ancient river which evolved this flood-plain; in the descent to Bear River the gravels are traceable down the sides of the cañon to the present stream bed. Beyond Bear River the road passes over Bear River Ridge at about the same

elevation as the summit of the road on Cape Mendocino Ridge, and the summit is again flat and plateau-like, though no gravels were observed. Beyond Bear River Ridge the sides of the lower portion of Eel River Valley are distinctly scored with stream terraces up to about 700 feet.

This thousand-foot baselevel bench mark, which is so persistent and so well defined, and other less prominent ones not here referred to, are clearly merely notches in the front of a plateau of much higher altitude. There are very distinct flat profiles at a general altitude of about 1,600 feet, and above this there rise somewhat higher low rounded profiles, and above this still and in contrast to all below are the sharper peaks of residual mountains. This language will, the writer fears, seem vague and indefinite, but in the absence of topographic surveys other than that of the exceedingly narrow strip given in the Coast Survey charts, it is difficult to be more precise. Enough has, however, been said to show that here in Humboldt County, where the broad peneplain effects of Mendocino and Sonoma Counties are lacking, there is still abundant evidence of very extensive uplift. A critical inspection of the topographic profiles, whose features are so difficult to express in words, and which must be seen to be fully appreciated, convinced the writer that they afford evidence of an uplift of from 1,600 to 1,700 feet, and there are strong suggestions that the full measure of the uplift may be as much as 2,100 feet.

Stream Topography.—The drainage features of the western slopes of the northern Coast Ranges of California loudly invite the attention of the devotees of the new science of geomorphology. They promise a rich harvest of facts illustrative of the principles of geomorphogeny to the student who will undertake their investigation. To see a problem in nature and to obtain some taste of the pleasures of its pursuit is one thing. To investigate the problem in all its richness of detail is another. The writer sadly confesses that he has only seen the problem, not investigated it. Any conception, therefore, of the stream topography which may be obtained from these notes is but a glimpse of the general product of processes of land sculpture, of whose detailed history, interactions, and adjustments we have none of the precise knowledge which inductive geomorphology now demands.

In general the stream topography is sufficiently advanced to bring into prominence the great control which geological structure has exerted upon the evolution of the drainage. A glance at the drainage map shows a very remarkable parallelism of all the main valleys of the western slope of the Coast Ranges. Not only are they parallel with one another, but their general direction is coincident with a remarkably straight stretch of shore line which extends from Point Arena to the head of Tomales Bay, and is continued as a strongly marked topographic feature through Ballenas Bay across the entrance of the Golden Gate. This remarkable line is the trace of a great fault which was established in pre-Miocene time, and was again, in post-Miocene time, functional as a plane of dislocation. This line is coincident with the general strike of the (earlier?) Mesozoic rocks which make up the greater part of the portion of the Coast Ranges here considered. Beyond Point Arena the shore bends away from this line and assumes a more northerly trend; and most of the rivers of the region emerge, therefore, on the coast obliquely. This great system of parallel valleys and dividing ridges is clearly an illustration of fully developed subsequent drainage on an extensive scale. Historically these subsequent streams are of two kinds. In the more mature portions of the original low, baseleveled tract which formed the surface of the block whose sculpture we are now discussing, the streams may be presumed to have wandered indifferently across the plain with a general direction normal to the coast. The tendency of the geological structure to control their courses prior to the plain condition may, as Davis suggests,* be assumed to have lost its effectiveness in the later stages of the old geomorphic cycle. In the early stages of the new cycle inaugurated by the uplift these water courses persisted as antecedent streams, and to them were added new consequent streams. As the relief became more marked, the influence of the underlying structure made itself felt. The dominant lines of weakness in the structure of the block began to appear, and along these lines subsequent streams were rapidly pushed. As the degradation proceeded, they became the main drainage lines. The antecedent and consequent streams dwindled, and many suffered atrophy. A few persisted as short

***Journal of Geology*, Vol. II, No. 1, p. 80.

trunk outlets for systems of far-reaching subsequent drainage. In this way we may account for a portion of the parallel streams which characterize the coast, and of which the Wallala is a notable example. But only a minor portion of these valleys is susceptible of such an explanation. The peneplain which existed prior to the inauguration of the uplift was, at best, only a coastal tract, which graded into a region of stronger relief. In this hilly country the stream courses were still completely under the control of the geological structure, and flowed in mature subsequent valleys. With the uplift this condition was bequeathed directly to the new cycle, and thus antecedent streams have persisted in their original subsequent courses, with various adjustments and migrations of divides, throughout the entire uplift. To this class belong the more important streams. The Eel River is a conspicuous example of the class.

There is also a third class of streams which are consequent upon the later stages of the uplift only. These are usually insignificant, but attain some little importance in middle Mendocino County, where, as before stated, the edge of the uplifted plateau has a gentle seaward slope. In these the consequent courses still dominate and the subsequent feeders are feeble. It may be remarked, also, that there is a coastal strip of later Mesozoic (Wallala) and Tertiary rocks whose structural lines do not always conform to those of the older rocks, but exhibit folds whose axes are normal to the coast. Many of the smaller streams which flow normal to the coast are subject to the control of this structure. With the exception of the lower stretch of the Eel River, which is discussed as a special case in the sequel, all of these streams, whatever be their history, flow in valleys or cañons which, if regard be paid chiefly to their lower portions, present a degree of advancement in the geomorphic cycle which is practically uniform throughout the region under consideration. The influence of the progressive character of the uplift is, however, apparent in the stream topography. The streams present near their mouths a less advanced topography than do their middle stretches. The cañons are narrower and more precipitous. The V-shaped profiles are much more acute. The divides are more indefinite, lying on plateaux rather than on ridge crests. This

relatively younger condition of the lower stretches of the cañons is clearly ascribable to the progressive emergence of the block. The uplift affects the profile of the stream first at its mouth, and the gradient which was established in the upper stretches for an older stage of the uplift may persist far into a succeeding stage. Degradation is thus less intense in the middle than in the lower stretches of the cañon, and the topography appears somewhat more mature. In reality, for the new baselevel, it lags behind that of the lower part of the stream, and is less mature.

Making just allowance for this apparent anomaly, due to the fact that the uplift, although for convenience considered as a single event, is really a series of movements, the writer has endeavored to estimate the degree of advancement of the region in the geomorphic cycle, using the terminology introduced by Davis. The features of the region as a whole seem to be those of a geomorphy which may fairly be classed as in late adolescence or early maturity. This statement, of course, breaks down entirely if consideration be given only to the seaward, terraced edge of the plateau; for, with reference to the broad, lower terraces, the topography is in its infancy. Indeed, when the tide is out on many parts of the coast, plateaux in embryo are visible, which await only another throe, similar to the many which have constituted the general uplift, to appear on the scene of the present cycle as the veriest squalling topographic sucklings. It also breaks down if consideration be confined to the head-waters of the streams, where the topography is much less advanced than in the middle stretches. It would be well if we could express the state of degradation of a block, or its position in the geomorphic cycle, in terms distinct from those used to express the degree of topographic advancement in the various portions of a stream valley. The general constancy of the character of the cañons, for analogous parts of the stream, under geological conditions which would favor uniform degradation, affords evidence indicative of a general uniformity of uplift.

EEL RIVER.

In traveling northward along the coast from Bodega Bay to Cape Mendocino the streams which are crossed all descend rapidly

from the Coast Ranges, and emerge through the narrow gorges immediately upon the shore. With the exception of the Russian River, they are comparatively short and unimportant, serving for the drainage of a narrow strip of country along the coast. They are alike, however, without exception, in being practically devoid of either deltas or flood-plains of corrasion. The latter are lacking because the erosive energy of the streams has been chiefly concerned with the sinking of their trenches, and little or no lateral corrasion of their cañons has yet been effected. Deltas are lacking because the fierce action of an open oceanic shore, with steep off shore profile, permits no embankment to extend beyond the line of the sea-cliffs; and there are no embayments within that line. When, therefore, a little beyond Cape Mendocino the north-bound traveler comes upon the valley of the Eel River, and discovers its beautiful broad flood-plain, he is little prepared for the contrast which its topography presents to that of the streams he has left behind him. When surprise gives way to reflection, a clear and correct perception is obtained of a radical difference in the conditions which have controlled the development of the topography in the two cases.

A cursory inspection of the flood-plain shows that its essential features are due, in all probability, to the lateral corrasion of the stream, and that it is not the surface of an embankment built up in a preëxisting valley by delta deposition. This being the case, it is evident that the causes which have differentiated the topography of this stream from that of all the others to the southward must be found in one or more of the following controlling conditions, viz.: (1) The great corrasive energy of the stream, due to its greater volume. (2) The longer local duration of the land at its present altitude relatively to sea level, or (3) the greater susceptibility to stream corrasion of the geological terrane through which it flows. A study of the region leads to the conclusion that the last of these is the effective cause. In its lower stretch the Eel River flows through a terrane which does not occur elsewhere along the portion of the coast now under consideration. The terrane is composed largely of soft, little coherent material, and yields readily to the attack of erosive forces. That the greater volume of the stream

cannot be held accountable for the relatively excessive corrasion, is evident from the fact that there are several small streams, comparable to those along the coast to the southward, which traverse the same terrane in the vicinity of Humboldt Bay, and which have carved out of it well-defined flood-plains. Also, the Eel River itself a little above Scotia is not confined to this terrane, but comes through harder formations similar to those of the coast; and where this is the case the low broad flood-plain is lacking. There is no evidence that the region of the mouth of the Eel River and Humboldt Bay has been for a longer time stationary than the coast to the southward. From the well-marked terraces, which score the sides of the valley, there is little doubt that it has been subject to the same general uplift as the coast adjacent to it on the south. The exceptional topography of the mouth of the Eel River thus directs attention to a formation which is unique for the portion of the coast with which we are now concerned. This formation is important in enabling us to establish the post-Pliocene age of a series of diastrophic movements which have affected the coast. A few observations as to its petrography, structure, and geological age, together with an incidental note upon its remarkable sculpture, are therefore here recorded.

THE WILD-CAT SERIES.

Distribution.—The region occupied by the terrane is commonly known to the people of Humboldt County as the "Wild-cat Country." If the name is at all suggestive of the weird, the chaotic, and the startling in landscape, it is certainly appropriate. The ruggedness and abruptness of relief in detail are remarkable. From Bear River Ridge, whence a general view of a characteristic portion of it may be obtained, it presents the aspect of a choppy sea of sharp hills and serrated ridges. These peaks and ridges rise to a maximum altitude of from 1,600 feet to 1,700 feet. Their crests bristle with open timber, much of it dead from the effects of forest fires; and their slopes are covered with shubbery, relieved with great open patches of yellow earth, where the process of land sculpture is in too vigorous operation to permit of the vegetation maintaining its foothold.

For the strata composing the terrane from which this strange topography has been evolved, it is proposed to use the name "Wild-cat Series." The areal distribution of the terrane and the lines of its demarkation from adjoining terranes are easily recognizable in the peculiarities of the sculpture. The extent of the terrane has not, however, been determined; but in a general way it may be said to occupy a large tract of Humboldt County to the north of Bear River Ridge, and east of Humboldt Bay. It is, doubtless, also, extensively developed in the coastal region northward of Eureka, and is known from fossils in the museum of the University of California, to be probably represented at Crescent City and Coos Bay.

The Ferndale Section.—This Wild-cat Series is exposed in a magnificently clear and unequivocal section on the ridge followed by the stage road in descending from the Bear River Ridge to Ferndale, on the southern edge of the Eel River flood-plain. The base of the series rests unconformably on a basement of Mesozoic sandstones at a point on the south side of Bear River Ridge about four and one-half miles south of Ferndale, the beds dipping northward at an angle of about 15°. The contact on the road is probably about 1,500 feet to 1,600 feet above sea level. From this point the road crosses the edges of the strata in a continuously ascending sequence to Ferndale, where the highest beds pass beneath the plain. The dip throughout this section is constantly northward (a little east of north) at angles varying from 15° to 25°. An enormous thickness of strata is thus exposed. Taking 15°, the lower limit of the angle of dip, a simple calculation gives 4,600 feet as a minimum value for the thickness of the series in this section. As the upper beds of the series, which have been truncated by the Eel River flood-plain, are not included in this estimate, and as the dip frequently exceeds 15°, the value for the thickness may safely be placed at over one mile.

Petrographically the strata consists of evenly-bedded yellow and brown clays, which on desiccation, weather spheroidally, silty clay shales, sandy clays, argillaceous sands, compact, but not firmly cemented, common yellow sandstones very feebly coherent, and pebbly conglomerates more or less firmly cemented. The clays are

most abundant at the bottom of the series; the compact sands and soft sandstones predominate towards the middle, and the gravel beds become prominent features only in the upper portion. Thin layers of marine shells in a fragmentary state are observed at various horizons, but owing to their frail condition they are difficult to collect.

The section thus briefly described is clearly the limb of a synclinal trough whose axis has a strike of a little south of east. Strata dipping southerly, and thus corresponding to the northern limb of the syncline, were observed to the north of Eel River, but the country was not sufficiently explored to ascertain whether the sequence was repeated. There seems to be, however, no reason to doubt that the structure is that of a simple syncline, and that the course of the Eel River near its mouth lies approximately in the synclinal axis.

Relation of Sculpture to Geology.—In examining this Ferndale section it becomes apparent that, although the result of the sculpture of the terrane is a seemingly chaotic assemblage of sharp peaks and ridges, the process of sculpture itself follows a well-known simple law. The erosion differs only in the intensity of its action from that of any other region of tilted stratified rocks. This intensity is due entirely to the excessive softness of the beds in general, and to the frequent alternation of slightly harder and softer rocks. In this particular belt of the Wild-cat Country the transverse drainage is northward to the Eel River across the edges of the northerly dipping beds. The terrane being of soft material, great numbers of such streams have been inaugurated. On either side of these drainage lines very numerous lines of subsequent drainage have been pushed laterally along the strike, the soft character of the strata enabling most of these to persist till they have met the advance of the corresponding cañons from the opposite side of the ridge, or have alone traversed the ridge. Qualitatively this is the normal process of land sculpture in all tilted sedimentary terranes. It differs, quantitatively, however, in the excessively large number of drainage lines which have been established, thus effecting a much more minute chopping up of the original block form. If, now, the terrane were composed of strata which persistently offered marked

differences in their resistance to erosion, the effect of such a process of sculpture would be an orderly alignment of the resultant peaks and ridges. But this condition obtains only to a limited extent in the Wild-cat Series. Differences in the hardness of the beds are slight, and it was apparently often some trivial accident that determined which of several soft beds abutting upon the transverse cañon was to be the line of subsequent drainage at that place. The same beds were not followed in the different transverse ridges nor always on opposite sides of the same ridge. Thus a disorderly arrangement of the resultant peaks and ridges has arisen.

From what has been said it will be apparent that the topography of the Wild-cat terrane differs essentially from that of the other terranes of the coast to the southward in the greater amount of degradation that has been effected. The sculpture has proceeded more rapidly and along more numerous lines of action. This fact would be expressed according to the method adopted by Davis, who has done so much to advance our knowledge of geomorphic evolution, by stating that the topography is older or more advanced than that where the sculpture has been less effective. Such a statement is true and is very graphic and useful; but it is not the whole truth, and is apt, therefore, to be somewhat misleading to those not fully cognizant of the facts of the case. It suggests the idea that the other more resistant terranes will in their evolution pass through a condition similar to that now presented by the Wild-cat terrane. This is not the case. The terrane of hard Mesozoic sandstones of the coast will never at any stage of its degradation yield a topography resembling the present topography of the Wild-cat terrane. When the former has reached the stage in the geomorphic cycle analogous to that which the latter has now attained, it will have a very different character. The difference in character will be radical, and will be due to geological conditions inherent in the constructional or block form. The variability of these conditions, moreover, is not only accountable for radical differences in topographic character at the same stage of the cycle, but also gives rise to different stages of degradation in the same block under the same erosive forces, acting for the same length of time. This latter point is important when topography is used as evidence in problems of

diastrophism, since, as in the case of the Eel River as compared with the rivers to the south of it, the stages of degradation may be so different as to suggest differential movements of adjoining regions, where none may have taken place. In view of these considerations it seems to the writer that, while the terminology which has been developed largely by Davis' writings is philosophical and admirable as far as it goes, it is yet defective in practically ignoring the important factor of relative susceptibility to degradation. In offering this criticism the writer does not shut his eyes to the difficulties that stand in the way of recognizing this factor in geomorphic terminology; and it may be possible that a simple nomenclature, defective to the extent indicated, will be found preferable to a more comprehensive but more cumbersome one. If, however, numerical formulæ be used to express the geomorphy with reference to the position in a graded scale, as recently suggested by Davis,* the factor might be introduced. Thus, it seems to the writer that if there are two portions of the same original block or constructional form which, in the same interval of time and for the same attitude of the land, have advanced differentially in the geomorphic cycle, the formulæ might be improved by introducing a factor for the rate of degradation. This factor would also indirectly express the character of the topography to a certain extent; for a rapid rate of degradation would indicate a soft terrane, and this would probably in general be found to involve a greater multiplicity of drainage lines and so a more choppy character of relief.

The Scotia Section.—The strata so well exposed in the Ferndale section may be followed along their strike to the vicinity of Scotia, and they doubtless extend for a considerable distance beyond this point, although they were not followed farther in this direction by the writer. Towards Scotia the beds become more arenaceous, grayer in color, more fossiliferous, and structurally they are inclined at much higher angles than in the Ferndale section. The more arenaceous character of the beds and the greater abundance of fossils, for the most part in an excellent state of preservation, indicate an approach to the shore line of the basin of deposition. On

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the right bank of the Eel River just below Scotia a very fine section is exposed in stream cliffs several hundred feet high. Here the rocks have a great thickness, comparable to that exposed in the Ferndale section, and the beds are dipping at much higher angles; and the belt of country underlain by them is correspondingly narrower.

Fossils.—Many of the Scotia beds teem with fossils, and in almost all parts of the section shells or fragments of shells may be detected, although in many cases they are difficult to remove from the rock in good condition. From the more favorable beds distributed through the section the writer found fossils which prove the Pliocene age of the series. A few Pliocene fossils had previously been known from Humboldt County and described by Gabb*, but the geological relations of the rocks in which they were found have never been discussed, and so far as the writer is aware no geologist has hitherto examined this interesting field. The few Pliocene fossils described by Gabb from Humboldt County undoubtedly came from the beds which are here designated as the Wild-cat Series. The collections of the writer from the Scotia section, together with some fossils found in the museum of the University of California and still others collected by Mr. A. Carpenter, were placed in the hands of Dr. J. C. Merriam for identification, and he has kindly furnished the following list of species:—

Cardium Meekianum, Gabb, Pl.
Pecten caurinum, Gould, Pl.—Rec.
Tapes Staleyi, Gabb, Pl.
Schizothærus Nuttalli, Con., Pl.—Rec.
Machæra patula, Dixon, Mio.—Rec.
Macoma edulis, Nutt., Mio.—Rec
Macoma expansa, Cpr., Mio.—Rec.
Macoma nasuta, Con., Mio.—Rec.
Solen rosaceus, Cpr., Mio.—Rec.
Standella falcata, Gould, Mio.—Rec.

*Geological Survey of California, Palæontology, Vol. II.

Thracia trapezoides, Con., Mio.—Pl.
Modiola multiradiata, Gabb, Mio.—Pl.
Mytilus Californianus, Con., Pl.—Rec.
Saxidomus gibbosus, Gabb, Pl.
Yoldia impressa, Con., Mio.—Rec.
Balanus sp.
Neptunea altispira, Gabb, Pl.
Neptunea tabulata, Baird, Mio.—Rec.
Drillia Voyi, Gabb, Pl.
Olivella bœtica, Cpr., Pl.—Rec.
Lunatia pallida, Brod. and Swb., Pl.—Rec.
Purpura canaliculata, Duclos, Pl.—Rec.
Columbella Richthofeni, Gabb, Pl.
Scutella interlineata, Stimp., Pl.
Cancer Breweri (?) Gabb, Mio.—Pl.
Nassa fossata, Gould, Mio.—Rec.
Cardium blandum, Gould, Mio.—Rec.
Psephis (Lordi ? Baird) Pl.—Rec.
Standella (planulata ? Con.), Pl.—Rec.
Natica clausa, Brod. and Swb., Pl.—Rec.
Fusus nov. sp., Pl.
Mactra sp.
Arca sulcicosta, Gabb, Pl.
Priscofusus Oregonensis, Con., Mio.—Pl.
Priscofusus devinctus, Con., Mio.—Pl.
Priene Oregonensis (?), Redf., Pl—Rec.

Of these 36 species only 14, or 39 per cent., are extinct. There are, moreover, 18 species which are not known in the Miocene. There is, therefore, no doubt as to the Pliocene age of the beds in which they are found.

Diastrophism.—From the observations above recorded it appears clear that (1) in Pliocene time the coast in the northern part of Cali-

fornia was greatly depressed and received a load of marine sediments at least a mile thick. (2) After the accumulation of the series it was folded in a syncline, the southern limb of which has been critically observed. *This syncline has its axis approximately normal to the trend of the coast.* Near the ocean it has gentle dips, but is sharply compressed and has high dips in the vicinity of Scotia. (3) The base of the series, as seen in the Ferndale section, must have been over a mile below sea level. It is now about 1,650 feet above that level.

This diastrophism appears, thus, to involve at least three distinct movements: (1) From the nature of the beds of the Wild-cat Series it is evident that the subsidence proceeded *pari passu* with the accumulation of the sediments. The movement was probably local. The doctrine of isostacy teaches a direct causal relation between the accumulation and the subsidence; but it is not clear that the accumulation may not have been an effect rather than a cause of the subsidence. (2) An orogenic movement which deformed the terrane and tilted the strata. This orogenic movement was local so far as the effects we are now considering are concerned, but may have been simply a local manifestation of a widespread orogenic activity inaugurated at the close of the Pliocene sedimentation on the west coast. (3) The third movement was the general or epeirogenic uplift of the coast. This movement, as has been shown, effected the uplift of an extensive coastal peneplain. This peneplain truncates the upturned edges of the Wild-cat strata and forms their upper hypsometric limit. The terrane is, moreover, terraced at various lower levels representing stages of the uplift. It is thus clear that the orogenic deformation of the terrane antedates the general uplift, and is separated from it by a portion at least of the time occupied in the evolution of the coastal peneplain. The fossils of the Wild-cat Series enable us to determine that the epeirogenic uplift of the coast was long subsequent to the deposition of the California Pliocene. The recognition of an orogenic disturbance following the accumulation of the Pliocene and antedating the epeirogenic uplift, suggests an explanation of some features of the coastal geomorphy which would otherwise be difficult to account for. If we suppose, and there is good warrant for the assumption,

that the essential features of the peneplain were developed during the Pliocene period of general depression, while the Wild-cat Series was in process of accumulation, and that the geomorphic cycle was locally interrupted in Humboldt County by the orogenic disturbances above referred to, while it persisted to the southward in Mendocino, Sonoma, and Marin Counties, we would have an explanation of the bold mountainous features of the more northern portion of the coast. The same movement which deformed the Wild-cat terrane probably broke up the peneplain by throwing up orogenic blocks and anteclinal arches. As the general uplift of the coast did not immediately ensue, there was time for the peneplain to extend in between the ridges of Humboldt County and to truncate the upturned edges of the Wild-cat strata before the more important epeirogenic movement set in. If, further, we suppose the same orogenic disturbance to have effected a synclinal sag of the coast of Mendocino County, we would have an adequate explanation of the gentle slope of the seaward edge of the coastal plateau, which is elsewhere remarkable for its abrupt character.

THE GOLDEN GATE SUBSIDENCE.

The region of the Bay of San Francisco and the coast adjacent to it, from Bodega Head to about the latitude of San Jose, a distance of 80 miles, possesses in a marked degree the geomorphic features of a sunken country. These features cause this portion of the coast to stand out in strong contrast to the other parts to the north and to the south of the sunken tract. These geomorphic characteristics are so strongly pronounced that a mere inspection of the maps has enabled Professor Davis to recognize the fact of the subsidence.* The features which afford such unmistakable evidence of depression of the land along this part of the coast are due to the flooding of stream valleys by the sea. As has been stated in a former part of this paper, all the streams of the coast from Bodega Bay to Cape Mendocino emerge immediately upon the shore line through narrow cañons, and there are no embayments in the shore line. South of Bodega Head the tide has invaded the lower

*Geographical Illustrations, p. 36, 1893.

stretches of the stream valleys, and made long, finger-like bays of them. The most notable of these flooded valleys is Tomales Bay, a narrow inlet parallel to the coast, about 15 miles long, and less than a mile in average width. The stream valley which now forms Tomales Bay was clearly a valley of subsequent drainage, and the transverse outlet was probably between Tomales Point and Bodega Head. Not only is the main valley flooded, but the lateral feeders are, also, in a more or less pronounced way invaded by the tide. The most striking of these is Walker's Creek, which presents all the characters of a fiord, being a narrow tidal inlet with high, precipitous walls on either side. The stream originally cut across a coastal ridge, having been probably a superimposed stream antecedent to at least the last thousand feet of uplift of the coast which preceded the subsidence that now floods its trench with the sea. Entering Bodega Bay, which is the extension of Tomales Bay, are two other similar creeks traversing the same ridge, the San Antonio and the Estero Americano, both of which allow the tide to extend several miles inland. Tomales Bay forms a natural trap for the shore drift, and this material, together with the delta material of the various small streams, is rapidly shoaling the bay, so that at present it is unfit for shipping.

The valley, which by flooding has thus become an inlet of the sea, could only have been eroded to its present depth during the latter part of the uplift, and the subsidence which caused the drowning of the valley was, therefore, practically subsequent to the uplift. There is, however, nothing to show that the elevatory movement which affected the coast as a whole had entirely ceased when the subsidence was inaugurated. The later movements of the uplift, and the earlier of the depression, may, therefore, have been coeval.

Even more significant of the recency of the depression are the flooded streams which end at the sand beach of Drake's Bay. These are called on the Coast Survey chart, Drake's Estero. These are finger-like inlets which are very clearly flooded stream cañons, representing a drainage convergent towards the south. *These cañons have effected the dissection of a plateau which is a marine wave-cut terrace, representing one of the later stages of the epeirogenic uplift of the coast.* Ballenas Bay is a similarly flooded valley which

has been cut down through a terrace of the immediately preceding uplift.

At the Golden Gate we have the flooded trench of the most important river on the Californian coast. The southern part of the Bay of San Francisco is the flooded valley of a subsequent tributary of that river. The structure which controlled the erosion was for the most part established by the post-Pliocene orogenic disturbances which deformed the Merced Series. That orogenic deformation was not the immediate cause of the flooding of San Francisco Bay, as might be inferred from a statement of the writer in a former paper.* The orogenic movement there referred to simply established structural conditions which controlled the erosion of the valley, that at a much later period was flooded by the sea. The full extent of this subsidence was not appreciated by the writer at the time the paper referred to was written, and, although the Bay of San Francisco was recognized as a sunken tract, it was not then clear that the subsidence was entirely subsequent to the general uplift of the coast. The limitation of the discussion to the features south of the Golden Gate, which was imposed upon the writer in the former paper by his lack of familiarity with the country to the north of that point, precluded his entering upon the question of the origin of the Bay of San Francisco.

At the Golden Gate the subsidence seems to have reached its climax, for to the southward the flooding of valleys gradually becomes less prominent, and cannot be said to be in evidence much south of the latitude of the southern end of the Bay of San Francisco. The bedrock of the valley is exposed at Coyote, 63 miles by rail from San Francisco, at an elevation of 250 feet above sea. Not only does the subsidence appear to culminate at the Golden Gate, but in the depth of the water in that passage we have, very probably, the measure of maximum subsidence. Generally the delta accumulation of the Sacramento River and other streams has kept pace with the submergence of the valley, and the greater part of the Bay of San Francisco is very shallow. In constricted places, however, where the currents are swift, the sediment has not accu-

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* This BULLETIN, Vol. I, No. 4, p. 159.

mulated to the same extent. The great volume of water, flowing in powerful currents through the Golden Gate with every incoming and outgoing tide, has been more effective for the transport of sediment than anywhere in the bay, or out beyond the heads; and as a consequence we have here the deepest water. The maximum depth of the Golden Gate is 63 fathoms, or 378 feet,* at its narrowest part, and if we assume this to represent the depth of the bedrock of the submerged Sacramento River, we have a direct measure of the subsidence. It may be argued that if the Golden Gate currents are powerful enough to transport sediments, they should be effective for corrasion, and that the deep trough in the Golden Gate may be due to removal of the bedrock by scouring. The fact, however, that the Coast Survey soundings show the presence of gravel and shells in the trough would indicate that such corrasion is not in progress. The question then arises as to how deep this layer of gravel and shells may be. In reply to this we have only conjecture. But from the nature of the material it is improbable that it is sufficiently thick to seriously affect the estimate of subsidence based upon the depth of the channel.

Within the Bay of San Francisco the deepest water is in the Raccoon Straits, where the lead shows 39 fathoms, or 234 feet, of water. This passage appears to be the landward prolongation of the Golden Gate, and may with great probability be accepted as portion of the ancient river trench. The region around the Bay of San Francisco abounds in minor but very significant evidences of submergence. A view of the bay in clear weather from the university buildings, looking towards San Rafael, is an ideal picture of a sunken tract, the islands of the bay being very clearly the summits and crests of a hilly portion of the former valley. Richardson's Bay is clearly a flooded valley. The various marshy embayments of the shore between Tiburon Point and the Carquinez Straits are also flooded valleys, which have become more or less completely silted up to the level of high tide. The tide extends far up Petaluma and Napa Creeks.

Outside of the entrance to the Golden Gate there is evidence of

* U. S. C. and G. Survey.

a similar order. Rodeo Lagoon is an incipient fiord, flooded only in its lower portion. Lake Merced is a flooded stream valley, the bottom of which is 10 feet below the tide. Half-moon Bay belongs to the same category of things. South of this point the tide invades the mouths of the streams to a small extent, and the subsidence is insignificant. It probably tapers out to a feather-edge before reaching Pigeon Point.

As regards the nature of the curve which delimits this sunken tract about the Bay of San Francisco, very little information is to hand. It is doubtless a synclinal sag, but it is not yet ascertained whether the synclinal axis lies approximately parallel to the coast or approximately normal to it, one or the other position being much more probable than any intermediate position. The rate of deformation in the direction parallel to the coast may be roughly ascertained as follows: The sag appears to extend a little beyond Bodega Head on the north but does not materially affect the Russian River. We may safely suppose it to feather out at the latter point. This is about 54 miles from the Golden Gate. The total sag at the Golden Gate being assumed to be 378 feet, this gives us a gradient for the tilted plane of 7 feet to the mile. This tilt should be recognizable in the terraces of the coast in the interval between these two points, but, unfortunately, for this particular portion of the coast, the terraces do not lend themselves to such a check. To the southward we have the bedrock of the ancient valley bottom exposed at Coyote, in the Santa Clara Valley, about 70 miles through the center of the valley in the probable course of a stream. Coyote is 630 feet above the bottom of the Golden Gate, which gives us a gradient of 9 feet to the mile. But to this a correction must be applied for the grade of the ancient stream bed, which may perhaps be placed at one foot to the mile. This would reduce the grade due to deformation to 8 feet to the mile; but a part of this is due not simply to the sag but also to a correlative buckling which is apparent in the arched form of the Santa Clara Valley, to which the writer has on a former occasion called attention,* but has not since farther investigated. It is safe to predict that the grade due to deformation

* This BULLETIN, Vol. I, No. 4.

will be found in the remnants of old baselevels which are traceable from the San Francisco Peninsula on the flanks of Montara Mountain southward to the Santa Cruz Range. If now we could obtain data for the measure of the tilting in a direction normal to the coast, it would be possible to locate the major and minor axes of the curve corresponding to the periphery of the sunken area, if the latter be not complicated by faulting. On this point we are not entirely without suggestion. The uplifted coastal peneplain is clearly discernible on the east side of the Bay of San Francisco as a dissected plateau represented by longitudinal and transverse ridges. These ridges, when viewed from a suitable standpoint, such as the upper flanks of Grizzly Peak, at Berkeley, fall into a slope, whose average maximum elevation is about 1,500 feet. The meridianal profile of this dissected plateau presents no marked sag. Its east and west profile, on the other hand, shows a decided slope towards the Bay of San Francisco. The presumption is, therefore, that the longer axis of the sunken area is parallel with the coast. The same conclusion is supported by the evidence from the Farallone Ridge, which appears as a series of islets running parallel with the coast about 21 miles out to sea, off the Golden Gate. A low terrace on the east side of San Pablo Bay (Bay of San Francisco) and at the Straits of Carquinez indicates an uplift at that locality which is subsequent to the subsidence. Its distribution is not yet known.

The subsidence which allowed the sea to invade the land through the Golden Gate seems to have been the first event of this kind since the general post-Pliocene uplift of the coast was inaugurated. If this be a fact, it is difficult to conceive the Sacramento River having any other relation to the Coast Ranges which it traverses than that of an antecedent stream. The Pliocene rocks around the Bay of San Francisco and Mount Diablo establish the presence of a marine Pliocene basin over this portion of the Coast Ranges. The late Tertiary rocks of northern Marin County in the vicinity of Tomales and Freestone may belong to the same basin. These Pliocene rocks were all affected by sharp orogenic deformation prior to the general uplift of the coast. It is improbable that the Sacramento drainage across the Coast Ranges antedates this movement. But, once established, it probably persisted throughout the whole

of the subsequent uplift of the coast, sinking its trench as the uplift proceeded. This being the case the waters of the ocean could not have had access to the Valley of California at any time during the uplift. It is, therefore, probable that there are no marine deposits of post-Pliocene age in the Valley of California.

It may, perhaps, be well to state here that in those portions of the coast which once served as areas of Pliocene sedimentation, as in the vicinity of the Bay of San Francisco, much of the geomorphic character was evolved in pre-Pliocene time, and has simply been revealed and modified by the stripping off of the Pliocene accumulations.

Associated with the subsidence which flooded the Bay of San Francisco there were probably other deformations of the crust which seem to have had an important influence on the drainage. The most notable instance of this kind is the shifting of the divides of the hydrographic basin of the Russian River. This stream once clearly flowed down through Petaluma Valley to the main drainage outlet at the Golden Gate. A low divide in the middle of the old valley now causes the drainage to flow westward at right angles to its former southerly course, and seek the coast by the present transverse route. The change in the drainage may be due to stream capture or to crustal warping. The latter is most probably the cause; but the problem has not yet been studied sufficiently.

SUMMARY.

From the foregoing observations and discussions it will be apparent that there is an essential harmony in the results here arrived at and those relative to the diastrophic record of the coast south of the Golden Gate, presented in a former paper.* The Wild-cat Series is the correlative of the Merced Series. Both seem to have accumulated under analogous conditions of a general coastal depression, accentuated locally by subsidence concomitant with the progress of sedimentation in the respective basins. Both, after attaining a thickness of at least one mile, were sharply deformed by orogenic movements to a similar degree. These movements were

*This BULLETIN, Vol. 1, No. 4.

probably not confined to these areas of accumulation of Pliocene sediments, but affected also other portions of the Coast Ranges, deforming the peneplain which had been in course of evolution in Pliocene time. Mount Diablo probably owes its upthrust to this epoch of disturbance. The bold ridges and peaks of western Humboldt County probably rose above the coastal peneplain at the same time; and the sag in the coast of middle Mendocino County may possibly be due to the same cause. These mountain-making movements were not, however, adequate to efface the peneplain, and the general altitude of the coast was not apparently affected. The base-leveling process continued and the peneplain was extended in between the bolder masses of the disturbed districts, and completely over the region occupied by the soft rocks of the Wild-cat Series. After this interval of encroachment of the old peneplain between the new orogenic blocks, the general uplift was inaugurated and has proceeded by stages down to the most recent times, the uplift in northern California being from 1,500 to 2,100 feet. This uplift from its extensive character can only be regarded as an epeirogenic movement. In so designating it, all allowance must be made for local inequalities of the movement. The ideal conception of an uplift strictly simultaneous in its action and uniform in its measure over any large tract of the earth's surface has probably been rarely or never realized in fact. The term used was probably not coined by its author for an ideal conception, but to describe phenomena which geologists meet with in practical work. The evidence from the geomorphy of the north Californian coast indicates a sufficient approximation to this ideal in so far as the measure of uplift is concerned; and the movement has been sufficiently simultaneous to inaugurate a new geomorphic cycle which is in a nearly uniform state of advancement all along the coast. The term epeirogenic seems, therefore, appropriate to the movement, though it may have involved local irregularity of action or of rate of action.

The Pliocene peneplain which was raised by the epeirogenic uplift seems to have differed in some respects in northern California from that of the southern Coast Ranges. In the latter, the plain was a baselevel partly of delta accumulation and partly of mountain truncation. In the former, it was essentially a plain of truncation,

and we have no evidence on the coast of preëxisting river valleys which were filled flush with delta material, as in the case of the San Benito Valley. The plain of truncation, also, is much more pronounced in northern California than to the south.

The peneplain here recognized as of Pliocene and in part of post-Pliocene development, is very probably the same as that which Mr. Diller has so ably and graphically described as extending in a deformed condition around the upper end of Sacramento Valley.* If this supposition should prove correct, there would seem to be necessity for a revision of the evidence upon which Mr. Diller bases his conclusion as to the Miocene age of the peneplain. On the coast there seems to be no reason for doubt as to its Pliocene and in part post-Pliocene age.

The next event in the diastrophic record, and perhaps the most interesting to Californians because of its recency, is the subsidence, to the extent of at least 378 feet, of the coast at the mouth of the Sacramento River, flooding the lower portion of the valley, giving us the magnificent harbor at San Francisco, and making of a river gorge the far-famed Golden Gate.

Seemingly the last event is a slight uplift in the vicinity of the Straits of Carquinez.

Geological Laboratory,
University of California, November, 1894.

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* *Journal of Geology*, Vol. II, No. 1, p. 32.

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ON

ANALCITE DIABASE

FROM

SAN LUIS OBISPO COUNTY, CALIFORNIA.

BY

HAROLD W. FAIRBANKS.

CONTENTS.

FIELD RELATIONS.

SAN LUIS OBISPO COUNTY is situated in the Coast Ranges of California, nearly midway between San Francisco and the southern boundary of the State. The topography is characterized by a series of mountain ranges extending northwest and southeast, constituting the Coast Range system. The geology of this region is

* These interesting rocks were discovered by the writer while engaged in field work for the State Mining Bureau. Their petrographic investigation was conducted in the geological laboratory of the University of California.

complex, but as yet it has been studied very little. In addition to the Tertiary and Cretaceous there is a pre-Cretaceous uncrystalline series and a basement complex of crystalline rocks. Many bodies of eruptives of various ages, and exhibiting a wide range in chemical composition, are found in different portions of the area.

One of the eruptive masses to be described lies in the extreme southeastern part of the county, in the range of desert mountains between the Carisa Plain and the Cuyamas Valley. The second is found on the western slope of the Santa Lucia Range, about seventy-five miles distant in a northwest direction. The third and least important occurs on the Eagle Ranch, in the Santa Lucia Range, about six miles west of the town of Santa Margarita.

Figure 1. Index Map.

The range in which the Cuyamas dike occurs is the watershed between the San Joaquin Valley and the Pacific Ocean, having an elevation of nearly 4,000 feet in places. Topographically it forms the connecting link between two granite ranges, the San Jose on the northwest and the San Emedio on the southeast. It rises quite abruptly from the broad and desert valley of the Cuyamas, presenting a most barren and forbidding aspect. Owing to the absence of vegetation, the general geological structure is easily made out. Although no fossils have been found in this range, yet the general nature of the formation and its relation to the known Chico-Tejon lying on the northwest and west, indicate that it is of Miocene age. The strata are but slightly consolidated, those of an argillaceous nature predominating. The eruptive body, as far as is known, lies wholly on the western side of the range. It begins nearly opposite the Spanish Ranch, about two miles from the valley, where

it has a width of about 1,000 feet, and extends in a northwest direction for a number of miles, gradually becoming narrower. The southern portion, exhibiting by far the greatest variation, and possessed of the most interest, is that from which the material for study was collected.

The second occurrence, which will be described in this paper, has a length of about twelve miles, extending northwest and southeast parallel to the Santa Lucia Range, on the slope of which it lies. The most southerly portion examined is exposed in a cut on the road from Templeton to Cayucos. The next point at which it was observed is at the foot of the grade on the road from Paso Robles to Cambria. At both these localities the sections are not good, and the rock is exceedingly friable and decomposed. Two miles northwest of the last locality, near the old Oceanic quicksilver mine, a deep cañon has been eroded across the eruptive body, giving an excellent section. At the southern exposure only one dike was noted. At the middle there are three, while in the cañon at the Oceanic mine there are four, the largest being nearly 300 feet wide. The dikes, as in the case of the Cuyamas occurrence, are inclosed in rocks of probable Miocene age.

CONTACT METAMORPHISM.

This phenomenon is very noticeable in the contact rocks of each of the occurrences. In that of the Cuyamas the strata have been tilted up vertically on each side of the dike, and distinctly changed for a distance of 100 feet. In an old tunnel, run in prospecting for silver, it is well shown; also in a cañon cutting across the dike farther north. At the latter locality a large mass of the country rock appears on the north wall of the cañon wholly inclosed in the eruptive.

Macroscopically the metamorphism appears to consist of an induration and blackening of the soft gray clays and calcareous sandstones, the clays having been changed to a black shining slate, and the incoherent sandstones to hard, slaty masses, giving a ringing sound when struck. The dark color is probably due to the effect of heat on the organic matter contained.

The nature of the inclosing rocks and the metamorphism

induced is very similar in the series of dikes near the Oceanic mine. Microscopically but little of interest appears in any of the slides prepared from the metamorphosed contact rocks. Mica, in the form of minute scales, seems to be the most important secondary mineral which can with certainty be made out. A recrystallization of the calcite has taken place in the sandstone forming individuals inclosing the other components, as shown by the luster on fresh surfaces of the rock.

MACROSCOPICAL CHARACTER OF THE CUYAMAS OCCURRENCE.

This eruptive mass consists of two distinct portions: (1) The main one, which is dark and fine grained; (2) ramifying dikes of later origin, much harder and lighter colored. The main body has the appearance of being very greatly decomposed. It is with difficulty, even in the deepest cañons, that hand specimens can be obtained which will not crumble upon a slight pressure. The mass is entirely free from any schistose tendency, but in places inclines to a shelly spheroidal structure. Such is the ease with which the rock disintegrates that the contour of the hills which it forms is not noticeably different from that of the unconsolidated Tertiary strata of a large part of the range.

The dikes which intersect the main body form the most interesting feature of the whole occurrence. They have a somewhat similar composition, but are generally much fresher. They cut the main dike in all directions, and are in most cases rather narrow, ranging from about six inches to two feet in width. They are more numerous near the western edge of the main mass, where there are several ten to eighteen feet wide. The most of these are hard and project above the crumbling rock inclosing them. As the latter weathers away, the dikes break up into masses of varying size and roll into the cañons. Occasionally one of these dikes is almost as dark and decomposed as the inclosing mass, but generally they are in sharp contrast with the latter. The very narrow ones are finer grained than the inclosing rock, but the broad ones are considerably coarser. All possess a granular structure which is as pronounced in the narrow ones as in the broad ones. It is probable that after the cooling of the upper portion of the main mass a strain

again occurred forcing up the still unconsolidated portions of the magma through fissures. That part already consolidated may have been warm, and so have permitted of a slow cooling of the secondary dikes, thus enabling them to take on a granular structure. The mineralogical composition of these dikes, compared with that of the main body, would suggest that either the conditions of cooling were different, or that there was a slight variation in chemical composition of the magma.

In a cañon which cuts across the main body about half a mile from its southern end, one of the largest of the secondary dikes is well exposed. The surface has been blasted off in search for silver, and good specimens for study were obtained. Near the edge of the dike there are irregular cavities, some of them two centimeters in diameter, partly filled with calcite and analcite. The analcite is also disseminated through the body of the rock in water clear grains, some six millimeters in diameter. They break with a splintery fracture and are frequently iridescent. In many cases this mineral is undergoing a change to a radial fibrous aggregate, determined by blowpipe tests to be natrolite. In some of the dikes the latter has almost entirely replaced the analcite. As a rule the feldspar and pyroxene show no striking peculiarities, although the former has a dull luster indicating decomposition. In the large dike, from which the most of the material was collected, the pyroxene is present in crystals which are sometimes fifteen millimeters long, and show a pronounced lamellar cleavage. These crystals are lustrous black on the outside, but within, a large proportion of them exhibit on part of the cleavage faces a bright silvery luster. The shining appearance is associated with the formation of a transversely fibrous structure. The boundary of this area is sharply defined from the black, lustrous outer portion of the crystal by a straight line of contact parallel to the long diameter of the crystal. What seem to be minute irregular fissures appear in the centers of these cleavage faces and extend the length of the crystals. While the silvery portion has an apparently fibrous structure, this is not exhibited when the crystal is split; but, instead, there is a strong tendency to the formation of thin, almost micaceous plates parallel to the diallagic cleavage.

MICROSCOPICAL PETROGRAPHY OF THE MAIN DIKE.

Owing to the exceedingly friable nature of the dark rock of the main body, only one section was prepared from it. Under the microscope this is seen to possess a holocrystalline diabase granular structure. The components, given in order of their separation, are: magnetite, olivine, feldspar, augite, and, last of all, the constituent which probably once occupied the angular areas, now filled by analcite, between the older constituents.

The feldspar is present in short lath-shaped and tabular forms, twinned according to the albite law. Twinning is seen in all except some tabular ones which show a decided zonal structure, the angle of extinction decreasing from the center outward. Many of the crystals are dotted with sharply defined isotropic areas. These, on farther investigation, proved to be analcite, and will be more particularly described in connection with the secondary dikes. The feldspars are also being invaded by a green to brown fibrous or granular material. This substance is particularly prominent in the angular spaces between the feldspars from which it has spread. Owing to the state of decomposition of the feldspars but few extinction angles were observed, and they were not generally symmetrical to the twinning plane; but it would seem from the fact that several were between twenty-five and thirty degrees that the feldspar must be fully as basic as labradorite.

Augite appears in allotriomorphic form, showing only slight signs of decay. It occurs either in large masses penetrated by and inclosing the feldspars, or in wedge-shaped areas between them. It is distributed quite irregularly over the slide. The color is a pale brownish green, no pleochroism being noticeable. Interpositions of dark dust-like particles appear along irregular planes, and are possibly of secondary origin. It is distinguished from the orthorhombic pyroxene by the high extinction angle on $\infty P \breve{\infty}$.

A reddish brown almost opaque substance is present in considerable abundance, occupying fully as much of the surface of the slide as the augite. In places it is not sharply differentiated from the matty green material, but in general has quite well-defined boundaries, which in several cases are hexagonal. In some of these

areas appear parallel partings, but the most have no structure and are surrounded by a dark opaque border of thickly aggregated magnetite particles. It would seem that there can be no doubt that these products indicate the original presence of olivine.

Magnetite is quite abundant as a primary constituent in the form of grains and long, slender rods. A chemical test showed the presence of titanium, while its magnetic properties distinguish it from ilmenite.

Analcite was evidently once quite abundant in the rock, filling wedge-shaped areas between the feldspars and augite. It has largely been replaced by the brown and green fibrous aggregates, whose exact nature is indeterminable. The larger areas still show in their centers an isotropic substance, which agrees in every particular with that proved to be analcite in the fresher dikes. The manner of occurrence of the analcite, as well as the structure of the rock, is shown in Plate 15, Fig. 1.

MICROSCOPICAL PETROGRAPHY OF THE SECONDARY DIKES.

Many sections were prepared from the large secondary dike which had been opened by prospectors. This is by far the freshest as well as most interesting of the secondary intrusions. The structure of the rock, as seen in thin section, is holocrystalline, approximately panidiomorphic. This dike, in common with all the secondary ones, contains no primary olivine; and the augite, instead of following the feldspar in order of crystallization, has either crystallized simultaneously or preceded it. In the latter case it exhibits large idiomorphic crystals.

Plagioclase.—The feldspar is present in the thin sections in short lath-shaped and tabular forms. The characteristic twinning is that according to the albite law, but in some instances it is found in combination with the pericline law. All the individuals show polysynthetic twinning in both broad and narrow plates, except the broad tabular forms, which are evidently cut parallel to $\infty P\breve{\infty}$, the composition plane, as they show the emergence of a bisectrix without the field of the microscope. The tabular forms exhibit a remarkable zonal structure. Many individuals were observed with a difference of 10°, and several as much as 18°, in the angle of

extinction between the inner and outer portions, the angle decreasing from the center outward. Twinned sections have a less marked zonal structure or none at all; a fact which might be explained by the more rapid growth of the crystal in $\infty P\breve{\infty}$ (010) than in the direction normal to that plane. There are scarcely any individuals but which are more or less decomposed, so that the correct determination of the extinction angles is difficult. The attempt to obtain cleavage plates which should show twinning was not successful, and the classification had to be based on sections cut haphazard. Taking all the sections together, about thirty-five individuals were found which extinguished either simultaneously or approximately so on either side of the twinning plane. A little more than half of these gave angles of extinction between 24° and 36°, the greater portion being less than 30°. This would seem to indicate, for a portion of the feldspar at least, a basicity not less than that of labradorite. The large variation in the angle of extinction on sections cut parallel to $\infty P\breve{\infty}$ must be interpreted as meaning an increasing acidity from the center outward. Judging from the manner of decomposition and general physical character, the feldspars must all belong to the same series, but it is difficult to assign their exact position on account of some apparently conflicting evidence. The paucity of calcite as a decomposition product in the rock, and the change to a soda rich mineral (analcite) indicate a soda feldspar; but the undoubtedly high extinction angle of a large proportion of the individuals would place them in the basic portion of the series. After digesting it long with concentrated hydrochloric acid the pulverized feldspar was apparently partly decomposed, thus allying it to labradorite. As a possible means of aiding the determination, a separation was attempted, using Klein's solution for the purpose of getting the specific gravity. A portion of the rock was pulverized sufficiently fine to be passed through an 80-mesh screen, and that which passed through the 100-mesh was rejected. Upon being placed in the solution the augite and magnetite immediately fell. The solution was then diluted until the separation of apparently pure feldspar was obtained. This was corroborated by a microscopic test. The specific gravity of this was found to be 2.511. A second separation was made at a greater density, using the material

which fell in the first trial. This gave a maximum specific gravity of 2.571, the powder in both cases appearing alike under the microscope. There was no point at which any large proportion of the feldspar came down. It fell little by little with increased dilution. The results obtained are so far below the specific gravity of any of the soda-lime feldspars that they can only be attributed to the dissemination of exceedingly minute particles of analcite through every portion.

Under the microscope the feldspars appear to be undergoing decomposition to several distinct products. The most prominent of these is a clear isotropic substance, identical in appearance with the analcite filling the angular spaces, even showing the same optical anomalies. In many instances this alteration has spread over nearly the whole crystal. In the case of some it has begun on the outside, in others from the center, leaving a mere shell. It is common to find that those crystals which contain much analcite are less altered to the other secondary products, such as kaolin and the green granular products. The analcite differs from that in the angular spaces between the crystals in being perfectly fresh. The analcite is often distributed through the crystals in angular sharply-defined areas, giving the appearance of a mosaic of the cuneiform characters of the quartz penetrations in graphic granite. (Plate 15, Fig. 2.) In these cases the remaining portions of the feldspar are perfectly clear and polarize brightly. When even but a small portion of the feldspar is left, it is perfectly clear. Those portions of the feldspars which join the angular areas of analcite, where the latter are more or less replaced by a green fibrous aggregate, are also invaded by the same along cracks and cleavage planes, and in extreme cases are almost wholly replaced by it. Decay of the feldspars to kaolin is also widespread. Sections made from many other dikes show much the same manner of decomposition for the feldspar. In every section the latter is more or less replaced by analcite, but kaolinic and green products are more characteristic.

Lamellar Pyroxene.—The pyroxenic component appears to be augite, but it exhibits some peculiar phenomena allying it to diallage. As distinguished from the orthorhombic pyroxenes, it gives

oblique extinction in the plane of the clinopinacoid, and the emergence of an optic axis in the orthopinacoidal section. The polarization colors are quite brilliant. It occurs partly in idiomorphic crystals and partly allotriomorphic with reference to the feldspar. It is very slightly pleochroic with pale brown to greenish tints. Numerous basal sections exhibit an octagonal form and very distinct prismatic cleavage. The idiomorphic individuals are elongated in the plane of the orthopinacoid to long tabular forms. Twinning is very common; in some individuals there are but two simple twins, in others a thin lamellar plate separates the two broad outer ones.

In addition to the twinning another divisional plane appears, which is so closely allied to it that, not until after close study and repeated examination, was it shown to be different. Twinning in augite takes place in the plane of the orthopinacoid, consequently sections cut in the plane of the clinopinacoid will extinguish symmetrically on either side of the trace of the composition plane, and, if the extinction angle is 45°, both will become dark at the same time. Twins cut perpendicularly to the prism will also extinguish simultaneously and parallel to the composition plane. This other parting in the augite of the Cuyamas dike takes place in the same plane as the twinning, and closely resembles it, but is distinguished by the fact that, in whatever position the section is cut, the two halves of the crystal extinguish simultaneously. Numerous individuals were examined which were cut in the clinopinacoid, or approximated it, and, with very few exceptions (twinned individuals), all extinguished simultaneously. The extinction angle was not 45°, and, consequently, as that is the only angle at which twins cut in that section could extinguish simultaneously, the phenomenon seen is not that of ordinary twinning. This plane, the trace of which is seen in the clinopinacoid and basal sections, is a very perfect one, geometrically considered. (Plate 15, Fig. 3.) It is distinguished by its regularity from ordinary cleavage, and is often so fine that it is inconspicuous. In some instances the parting does not extend to the borders of the crystal, and still more rarely there was observed a short parallel parting. A close examination of this plane with high powers showed that it was not possible to

consider it as being due to the interposition of an exceedingly thin lamellar twin, in which case the two outer twins would extinguish simultaneously. It could not be considered of secondary origin, for it is fully as prominent in the freshest crystals, seeming to have no connection with a cloudy fibrous appearance in many of them. It is quite possible, however, that it represents the junction of two individuals with the same molecular orientation, and that, instead of ordinary twinning, in which alternate individuals are reversed, in this case the reversion did not take place. An approximately basal section was observed in one slide in which normal twinning appeared, the two halves not extinguishing simultaneously, while in addition one of the halves contained the trace of this peculiar parting. This plane divided it into two slightly unequal portions, both of which showed the same polarization tints and extinguished simultaneously.

Another remarkable feature of the augite, quite distinct from the last, is the very perfect diallagic cleavage and the silvery lustered interior portion. In thin section the latter is indicated by fibrous cloudy areas, somewhat irregular in shape and generally confined to the central portion of the crystal. Plate 15, Fig. 3, is a good illustration of this decomposition. A cleavage plate parallel to the orthopinacoidal parting was obtained, showing the nature of the alteration. The fibers lie transverse to the *c* axis, fading out toward the periphery, their extremities being terminated by the traces of the planes of the prismatic cleavage. (Plate 15, Fig. 4.) In the hand specimen this cleavage is very strongly pronounced, and, judging from the manner in which the crystals split, it is not confined to one plane, but may be developed in any portion of the crystal. The perfect cleavage and silvery luster of the augite individuals in the hand specimen is one of the most striking features of the rock. This phenomenon undoubtedly represents the beginning of a change to diallage, but, instead of starting from the outside, as is usually the case, the alteration has commenced at the center, and the fibration has taken place transversely instead of longitudinally.

Analcite.—The first thing in the hand specimen that attracts one's attention is the presence of clear, glassy grains, with a faint iridescent luster. Under the microscope they are found to be

almost isotropic, exhibiting generally the faint double refraction in the form of stripes, so characteristic of analcite. The mineral proved to be soluble in hydrochloric acid, and the solution upon evaporation to dryness left crystals of sodium chloride. It was somewhat more difficultly fusible than is stated to be the case with analcite in the works upon blowpipe analysis. The specific gravity ascertained by Klein's solution was 2.266. The analcite occurs under four different conditions in the rock, namely: (1) Lining the sides of cavities frequently two centimeters in longest diameter; (2) filling the angular spaces between the divergent feldspar crystals, spaces from microscopic size up to eight millimeters in diameter; (3) replacing the feldspars; and (4) in one of the dikes, in the form of hexagonal or rounded grains partly inclosed within the feldspars. It is possible that the larger cavities about which the analcite is crystallized are of secondary origin, as they occur only locally and in portions of the rock which are most decomposed, but they do not differ materially in character from some of the larger spaces entirely filled with analcite, on which, as in the case of the crystals lining the cavities, striations appear. Faces of the trapezohedron, the common crystallographic form of analcite, were observed on some of the crystals lining these cavities.

At the termination of the crystallization of the feldspar and augite sharply angular areas were left between the divergent crystals, which are now filled with analcite and its decomposition products. To account for the presence of the analcite we have to adopt one of four hypotheses: The possibility of its being primary, of its derivation from the feldspar, of its resulting from the decay of some unknown soda-rich mineral, or of its introduction into the rock subsequent to its solidification. Of the first there is no confirmatory evidence whatever. With one exception analcite has always been considered of secondary origin. The analcite of the basalt described by Lindgren,* from Montana, is considered by him as primary. This opinion is based on the fresh condition of the rock and the predominance of hexagonal sections among those

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*Eruptive Rocks from Montana, Proc. Cal. Acad. Sci., Vol. III., 1891, p. 55.

which are idiomorphic. He says: "Nepheline could, of course, not be the mineral from which the analcite might be derived, the form of the crystals prohibiting that supposition." It would appear to the writer that this could be no objection, as nepheline frequently shows hexagonal sections. No evidence is at hand to support the view of its subsequent introduction into the rock. Its apparently uniform distribution through the whole of the extensive eruptive mass which has not been fissured or sheared makes this view seem utterly untenable. Although no direct evidence appears in the rocks under discussion in favor of the supposition of the derivation of the analcite from an unknown soda-rich mineral, it seems probable that such is its origin. The test for sulphur gave a negative result, while that for chlorine resulted in only a trace. The minerals of the sodalite group are thus excluded. Nepheline is the only remaining soda mineral from which it might be derived, and it will be shown how closely the rock resembles some from other localities known to contain nepheline or eleolite. A slide from one of the smaller dikes exhibited a number of areas of an isotropic substance partly inclosed in the feldspars and idiomorphic with reference to them. Several of these have a rude hexagonal outline, and one in particular is very regularly hexagonal. (Plate 15, Fig. 5.) They are not apatite, as is shown by the partial decomposition and absence of an interference figure, and are, without doubt, referable to analcite. Scattered through them are small crystals of a substance which has the character of calcite. Analcite also occurs in the same rock, in wedge-shaped areas between the feldspars. In the one case the analcite has certainly replaced a soda mineral, perhaps nepheline, and in the other its origin is doubtful. It is possible a part of the nepheline in the dike crystallized before the feldspar, and the remaining portion, if such existed, as the last constituent. The feldspar, judging from the extinction angle, all belongs in the basic portion of the series. Even on the supposition that it were albite of normal composition, and form fifty per cent. of the rock, the percentage of soda which should be present in the rock would fall below that given in the analysis. Confirmatory, then, of the view of the original derivation of the analcite from nepheline is the relative basicity of the feldspar and the high per-

centage of soda, as shown by the bausch analysis. Opposed is the low percentage of lime, and the possibility that the feldspar either contains a sufficient amount of soda, or that it has been introduced subsequently. In the light of all the facts it seems to the writer that the hypothesis of the derivation of the analcite from nepheline has the most in its favor, although several things are still unexplained.

The rock as a whole has close affinities with those of the disputed teschenite group, but contains no mica or hornblende. Rosenbusch* holds that the analcite in rocks of this class, in which nepheline cannot be detected, has nevertheless been derived from nepheline, that if it were not derived from nepheline the rock must have had originally a remarkable porous structure, and that he does not see how the alteration of a lime-rich feldspar can result in a soda zeolite. Such a porous structure (miarolitic) as must have existed in the rocks under discussion, had the wedge-shaped areas been left empty at the close of the solidification of the magma, is unknown in rocks of the diabase type.

Rohrbach,† who subsequently studied the rocks termed teschenites by Tschermak, was unable to find nepheline in any of them, and reached the conclusion that the analcite owed its origin to the feldspar. His description of the manner of the occurrence of the analcite is very similar to that observed in the Cuyamas eruptive. He mentions analcite as present in angular spaces between the feldspars, also in shreds and veins with sharply defined boundaries replacing them, pseudomorphs of analcite after feldspar also being noted. The analyses given by him show, however, a very much less amount of soda than is found in the rock under discussion.

The feldspar in the rock studied by Rohrbach exhibited a zonal structure, and he considered that it represented all degrees of basicity from anorthite to albite. If this view is correct, the feldspar would furnish quite a percentage of soda. Macpherson, in his study of the teschenites of Spain, as cited by Rosenbusch, reached much the same conclusion as Rohrbach.

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*Mikroskopische Physiographie der Massigen Gestine, p. 253.

†Ueber die Eruptivgestine in gebite der Schlesich-Mahrischen Kreideformation. T. M. P. M., 1886.

Teall* describes a very similar rock consisting of prismatic augite, feldspar much altered, analcite, natrolite, magnetite, brown mica, and green decomposition products. He says: "Unless soda has been introduced, the abundance of analcite would imply either the existence of nepheline or of a soda-lime rather than a lime-soda feldspar."

The description given by Williams† of the eleolite syenite rocks of Arkansas is very interesting in connection with the study of this rock. Several short extracts will be given to illustrate the structural affinities of those rocks with the Cuyamas eruptive. He says: "Eleolite never occurs in this rock in idiomorphic crystals, but always in wedge-shaped or polyhedral masses which take their exterior form from the minerals by which they are surrounded. * * * It is a very common thing to find this mineral altered to analcite; in some cases so complete has been this change that in many sections no remnant of the original substance can be found. * * * The analcite seems to have eaten into the feldspar wherever it could get a chance, and many feldspars may be found whose centers have become almost entirely changed into analcite, while others have been eaten away on one side, the rest remaining intact." Williams‡ also describes a miarolitic structure in the Magnet Cove eleolite syenite. The rock is much decomposed and the eleolite has nearly disappeared. "It contains many cavities into which the feldspar crystals extend and show by their perfect crystalline forms that these spaces were originally empty or were filled with some late formed mineral which has since been decomposed." This description will apply to both the Cuyamas and Oceanic dikes, both augite and feldspar projecting into the analcite areas with perfect idiomorphic forms. (Plate 15, Fig. 6.) It is probable that these dykes were not originally miarolitic, but that the spaces must have been filled by some late formed mineral rich in alkali. It would hardly be reasonable to suppose that a miarolitic structure existed so uniformly in all the dikes described, both large and small. Carry a step farther the decomposition of the eleolite of the Arkansas rocks, and we have a

*British Petrography, p. 191.

†Arkansas Geological Survey, Igneous Rocks, pp. 66, 79.

‡*Ibid.*, p. 232.

remarkable parallel with that of the best preserved of the rocks described in this paper.

Wolff* describes a rock which he terms a tephrite, from the Crazy Mountains, Montana, in which the nepheline is said to lie between the feldspars in imperfect crystals or to fill triangular spaces. In another publication† he describes acmite trachytes from the same region in which nepheline occurs, filling angular areas between the other components.

The third important condition under which the analcite occurs, that of replacing the feldspars, has already been described. The change to analcite does not seem to have taken place from the wedge-shaped areas between the feldspars, but to have gone on independently in various portions of the crystals. The appearance in many places, where the isotropic areas are so sharply defined, is that of a paramorphic rather than a chemical change. This replacement of feldspar by analcite has been noted in all the rocks of this class, as well as in the eleolite syenites of Arkansas and the nepheline rocks of Montana, and does not seem to depend on the percentage of soda in the feldspar. This phenomenon seems to be mostly confined to rocks rich in nepheline and related minerals, or to those in which they are supposed to have existed.

The analcite occupying the wedge-shaped areas is undergoing decomposition to a green fibrous aggregate. The fibers extend inward from the outer edge, often aggregated in radial tufts. They are non-pleochroic, polarize quite brilliantly in greenish to reddish tints and extinguish parallel to their long diameters. These fibers often exhibit an undulate form and terminate in the analcite in slender branching needles. They are almost colorless toward their extremities, but being doubly refracting are strongly marked from the analcite under crossed nicols. After treatment with hydrochloric acid and fuchsine, these fibers were stained a deep purple. A specific determination was found to be impossible on account of the small dimensions and lack of crystal outlines.

In many of the sections, especially those from the smaller dikes,

*Notes on the Petrography of the Crazy Mountains. North. Trans. Survey.

†Acmite Trachyte from the Crazy Mountains, Montana. Bull. Museum Comp. Zoölogy, Harvard College, Vol. XVI.

the analcite is largely replaced by natrolite in radial aggregates. It also occurs in veins traversing the rock.

Secondary Minerals in the Analcite.—The polyhedral or wedge-shaped areas of analcite contain two secondary minerals in a fresh condition. One, having the character of prehnite, occurs in clear grains and idiomorphic crystals projecting into the analcite from the borders or wholly inclosed in it. The other is probably feldspar, bordering the analcite and apparently replacing that substance.

The prehnite crystals are in some cases more than a millimeter in diameter, but generally smaller, and are found in many of the analcite areas of all the slides prepared from the large dike. (Plate 16, Figs. 1 and 2.) It is as clear and colorless as the analcite, but in ordinary light is distinguished from the latter by the high index of refraction, producing an apparently rough surface and high relief. The polarization colors are very brilliant. The optical anomalies often seen in prehnite do not appear. The form of the idiomorphic individuals is commonly hexagonal or octagonal. No trace of cleavage is to be seen. Two sections were obtained cut perpendicular to a bisectrix. Each of these showed a bi-axial interference figure, in which the dispersion was apparently symmetrical with reference both to the plane of the bisectrices and that perpendicular to it. When the crystallographic boundaries are present the extinction is parallel to one edge, indicating an orthorhombic mineral. One of the sections referred to gave a negative, the other a positive sign. The dispersion is that given for prehnite, red being less than blue. Several treatments with hot hydrochloric and sulphuric acids failed to decompose it; the only effect produced seemed to be a roughening of the surface and the appearance of irregular cracks extending inward from portions of the surface.

Owing to the minute size of the crystals, and to the fact that the optical properties of this mineral are identical with those of olivine, much difficulty was experienced in making a positive determination. The greater resistance of the mineral under discussion to acids and the unlikelihood of olivine occurring as a secondary product, made the determination in favor of prehnite probable. To make this certain a few grains were obtained perfectly free from the other components and treated with hydrofluosilicic acid. This developed

characteristic spindle-shaped crystals of fluosilicate of calcium. As certain varieties of olivine contain lime, it was necessary to determine whether alumina was present or not, prehnite being a lime alumina silicate, while olivine contains no alumina. For this purpose Behren's method was used. A few very minute grains were obtained, and, after being reduced to a powder, were treated with hydrofluoric acid. This decomposed the mineral, and upon evaporation a few drops of pure sulphuric acid were added and the mass reduced to a sulphate. After evaporation the residue was diluted slightly with water and the solution was ready for examination. A microscopic examination showed it to be filled with minute rod-like crystals of gypsum. A drop of cæsium sulphate was added to part of the solution on a glass slide. At first no reaction took place, but upon standing a day numerous small crystals of cæsium alum separated out, having the form of very perfect octahedra. This reaction showed that the mineral was not olivine, and inasmuch as lime was abundant and magnesia not definitely recognized, the determination of the mineral as prehnite was considered as correct. As a check upon the above, the specific gravity of several grains was determined by Klein's solution and found to be 2.894, the specific gravity of prehnite ranging from 2.80 to 3.

Many of the analcite areas contain large numbers of the prehnite individuals, only a part of which are idiomorphic, and in rare instances a single crystal was observed nearly filling a wedge-shaped area (Plate 15, Fig. 6), being partially allotriomorphic. The perfect idiomorphic boundaries of those individuals lying farther within the analcite, and the more irregular granular form of the smaller ones clustered near the outer edge, and their lack of attachment to the feldspars bounding the analcite, suggest very strongly their formation within the analcite and not in a cavity. Many instances appear of prehnite crystals wholly separated from the feldspar by the analcite, and in some cases by secondary feldspar. The green fibrous material eating into the analcite has slightly affected a portion of the prehnite crystals.

The question may arise as to whether the idiomorphic outline of many of the prehnite individuals does not make their formation from the analcite impossible. It might seem more likely that they

grew as druses in originally empty spaces in the rock. This would of course affect the question of the original presence of nepheline. In the first place it may be said that the condition of occurrence of several of the minerals of this rock including the prehnite is quite peculiar. It seems to the writer probable that the prehnite was formed either during the alteration of the nepheline, from which the analcite is supposed to have been derived, or directly from the analcite itself. In many of the feldspar crystals the alteration to analcite has left as sharply defined rectilinear lines as are shown to exist between the analcite and the prehnite, but in the former case there is no tendency to the formation of crystal boundaries. The writer does not deny that there may have been open spaces left in portions of the rock mass at the time of solidification; the presence of analcite partly filling some of these in the largest secondary dike supports that view.

The discussion of the question concerning the original presence of nepheline has been given in another place. In addition it might be said that the existence of a similar structure (the polyhedral areas filled with analcite) in all the known bodies of rock of this type, and in this type only, in the Coast Ranges—bodies of varied size, which must have solidified under different conditions—is inconceivable unless we postulate some original inherent peculiarity of composition. This is best illustrated in the case of the Cuyamas eruptive. The polyhedral areas filled with analcite are found to occur in a similar manner in the large primary mass, which is a thousand feet across, as in the numerous secondary dikes from four inches to twenty feet wide. It is hardly possible that similar conditions of solidification could have existed in bodies of such greatly diverse size. While the writer does not hold that the original presence of nepheline can be demonstrated (unless in the case of one dike in which hexagonal areas of analcite occur), yet, taking everything into consideration, there seem to be fewer difficulties opposed to that view than to any other.

The other mineral, supposed to be feldspar, is found bordering the analcite and growing inward. It generally occurs as an irregular border of microscopic proportions. Sometimes the outer edge is wavy (Plate 16, Fig. 3), at others rectangularly serrated. It is

perfectly clear, does not polarize brightly, and is unaffected by acids. The large areas show the dark arm of a biaxial interference figure. The manner of occurrence would lead to the belief that it is a soda-rich feldspar. Several instances were observed of a twinned feldspar, fresh in appearance, and showing a small extinction angle, which was also inclosed in the analcite and apparently of secondary origin. One of these has a regular and well-defined crystal boundary. Secondary feldspar is also found in and on the edges of the primary feldspar.

Titaniferous Magnetite.—The oldest separation from the magma is magnetic iron oxide containing titanium. It occurs in irregular grains, hexagonal and rectangular forms, and long slender rods sometimes united in skeleton crystals. These penetrate all the other primary components of the rock. In some of the hand specimens these rods are plainly visible, being a millimeter or less in width and ten to fifteen millimeters long. It is present in all the dikes, but the proportion varies greatly. Plate 16, Fig. 4, illustrates a rock in which there is an uncommonly high percentage of this mineral.

CHEMICAL CHARACTER.

The writer is indebted to Mr. V. Lenher, of the Department of Chemistry of the University of California, for the analysis (I) of the large secondary dike in the Cuyamas region given below. There is inserted for comparison, an analysis (II) given by Rohrbach* of a typical teschenite; of a theralite (III) by Wolff†; and of a plagioclastic eleolite syenite (IV) from Arkansas.‡

*T. M. P. M. 1886.

†Notes on the Petrography of the Crazy Mountains, Montana.

‡Geological Survey of Arkansas. Igneous Rocks, p. 139.

	I.	II.	III.	IV.
SiO_2	50.55	47.41	43.175	58.74
Al_2O_3	20.48	18.65	15.236	20.85
Fe_2O_3	2.66	10.21	7.607	4.15
FeO	4.02		2.668	.....
CaO	7.30	7.17	10.633	0.36
MgO	4.24	5.06	5.810	0.22
K_2O	2.27	2.06	4.070	4.23
Na_2O	8.37	4.90	5.680	9.72
SO_3	.....	.....	0.940	.....
H_2O	.44	5.05	3.571	1.82
Cl	Trace	.....	......	.....
	100.33	100.52	99.390	100.09

It is very difficult to arrive at any conclusion as to the composition of the different components of Cuyamas dike from the analysis. The rock is remarkable for the high percentage of alkalies and alumina and the low percentage of calcium. The proportion of soda is too great for even a soda feldspar, although the high extinction angles forbid that supposition. The presence of so much potash with no potash feldspar is another thing which it is difficult to explain. If a portion of it is contained in the analcite, that would favor the view of the derivation of that mineral from nepheline, which always contains potash. The percentage of calcium is too low for the estimated proportion of augite in the rock, unless it be of very peculiar composition, to say nothing of that required for the feldspars with so high an extinction angle. The analysis given by Rohrbach is of a rock containing labradorite feldspar. The amount of potash and calcium agrees very closely with that of the Cuyamas dike, but the soda is less. The feldspar in the Arkansas rock, according to Williams, lies between albite and labradorite, although the extinction angles correspond to labradorite. This rock contains twenty-five per cent of eleolite, but the analysis shows a comparatively small increase of soda over that of the Cuyamas dike. Williams considers the rock closely allied to the theralites in mineralogical composition.

Although the actual proof is not possible, it seems to the writer that the conclusion is reasonable that some primary soda silicate (probably nepheline) formerly occupied the wedge-shaped areas. The description given by Rosenbusch and others of the teschenites corresponds very closely with the facts observed in the rocks which form the subject of this paper.

OCEANIC DIKES.

The most important development of this series of dikes is near the Oceanic quicksilver mine, six miles east of Cambria. Two to four dikes of varying width and separated by narrow strips of upturned Tertiary strata were traced for at least twelve miles. There is a great similarity in all, and they have undoubtedly issued from one parent magma. At one locality an oil well was sunk nearly seven hundred feet in a strip of Tertiary strata lying between two of these dikes. In the bottom a crystalline rock was encountered which in all probability marks the point at which junction takes place. The degree of decomposition of these dikes appears to be very great. Except in the bottom of the cañons the rock is scarcely more coherent than the main body of the Cuyamas dike. At the foot of the grade leading from Cambria across the mountains, there are shown some remarkable examples of shelly spheroidal weathering. Many of the spheroids are a foot in diameter with clayey matter between them, and peel off in very regular concentric shells, one-third of an inch in thickness down to a more solid core.

A microscopic study of these rocks confirmed to a considerable degree the appearance of decomposition. In a general way there are two macroscopic differences, the lighter colored facies in structure and appearance much resembling the Cuyamas dike, except that no analcite is visible to the unaided eye; and the dark-colored facies, very rich in iron, in which the individual components cannot be determined without the microscope. The most of the lighter-colored specimens were collected from the most westerly dike. Sections made from this dike showed the existence of feldspar, augite, olivine decomposed to serpentine, analcite, magnetite, and green decomposition products. The structure is typically diabase granular, the feldspar crystals penetrating and frequently almost

isolating portions of the same augite individual. The feldspars show twinning (albite law) and high angle of extinction in a manner similar to that of the Cuyamas dike. Tabular sections are less abundant, lath-shaped forms predominating. But few feldspar individuals have a fresh appearance, having been changed to kaolinic matter or penetrated and largely replaced by green decomposition products, originating in the olivine and angular analcite areas. A replacement of the feldspars by analcite has taken place in a manner similar to that before described, but it is less pronounced. This change is more noticeable in the fresher individuals.

The augite is similar to that before described, but more rarely shows crystal forms and never that distinct orthopinacoidal cleavage. In most specimens it is the freshest component of the rock.

To the decay of the olivine is due in part the alteration of the other components. All sections show areas of green matty and granular material, which, from the frequent hexagonal forms with clear centers and dark borders, filled with magnetite granules, and very pronounced reticulated structure, are judged to represent olivine. The centers are in many cases brilliantly polarizing and intersected by clear rectangular lines. The decomposition products are serpentinous in character.

There are other sharply angular areas between the feldspars filled with green matty and fibrous material, which, it is believed, has replaced analcite, as in places that isotropic mineral still remains. (Plate 16, Fig. 5.) On account of the decomposition of the analcite filling these wedge-shaped areas, it was distinctly determined in only two slides, but it was undoubtedly present at one time in all. The freshest portion of the dike has a very peculiar structure, crumbling to spherical bodies fifteen to twenty millimeters in diameter. Titaniferous magnetite is present in this dike, as before described, in the form of grains and long rods.

In the dark and fine-grained types confined to the three easterly dikes, as in the one just described, it is often impossible to obtain coherent specimens in place, and the exact position in the dike of many studied is unknown. Nearly all the sections made from these rocks show a much fresher condition of the feldspar and olivine. The former are more lath shaped, and high angles of

extinction are common. The olivine is more abundant, but in manner of decay resembles that just described. The decomposition products of this mineral have so penetrated the angular spaces, as well as the feldspars themselves, that the presence of analcite was not detected. Magnetite is very abundant, both as a primary constituent and as secondary dust, in the olivine decomposition products. Opaque granules are numerous in the feldspar of one slide. In another it is penetrated by minute clear rods, probably apatite.

There is one type of the dark rocks of uncommon interest. As usual the feldspar predominates, but it is comparatively fresh. The augite is also fresh. The amount of serpentinous matter showing the appearance of olivine decomposition is large. This serpentinous substance has spread through the rock, almost isolating individual feldspar crystals. It also appears in angular spaces of various sizes, spaces which resemble those occupied by analcite in the other specimens. Portions of these spaces not filled with this green matty material are occupied by a clear substance in the form of aggregated individuals, showing the polarization of calcite. Treated with dilute acid this is decomposed with effervescence. Lying either in the green products, partially in the calcite, or on the borders of the angular spaces, are spherulites of a very peculiar character. (Plate 16, Fig. 6.) They generally possess a dark center, around which are placed wedge-shaped plates to form an almost perfect sphere when not interfered with. The outer contour of the spherulites is bordered by a dark crenulate line, a short distance within which is another crenulate circle formed of two lines. Under crossed nicols a dark cross is seen, which even extends at times beyond the boundary of the spherulite proper to radially arranged calcite individuals. The spherulite itself has a very pale yellow color, while the carbonate is colorless. After treatment with hot concentrated sulphuric acid and staining with fuchsin, the centers and borders only are seen to have been affected. The invariable position of the spherulites and their association with calcite would indicate that they were not formed primarily in a glassy portion of the rock, but are secondary products partly replacing some easily decomposable primary mineral (possibly one of the sodalite group). No known

secondary spherulites except chalcedony would resist the action of acids, and these cannot be referred to that substance.

EAGLE RANCH OCCURRENCE.*

A small dike, which should undoubtedly be classed with the analcite diabases above described, is found on the Eagle Ranch, in the heart of the Santa Lucia Range. It outcrops in the center of a conical hill, formed of lower Cretaceous sandstone and shale. Microscopically it very closely resembles the secondary dikes of the Cuyamas eruptive, but is more decomposed, no analcite being visible. The feldspar has a dull luster, but the augite appears quite fresh. Much greenish material is scattered through the rock. The structure is diabase granular.

Microscopically the specimens appear very much decomposed. The short lath-shaped feldspars show traces of polysynthetic twinning, but are completely decomposed to cloudy kaolinic masses. It is not possible to measure the extinction angle. The augite is fresh in some specimens, in others considerably clouded. It has a pale brownish color, and shows no pleochroism. A pale green substance, somewhat fibrous, is very abundant in the thin section. It fills angular areas between the feldspars, and in many cases has invaded the latter. This substance closely resembles that which has replaced the analcite in the more altered of the dikes already described. In its manner of occurrence it is precisely similar. No analcite was detected in any of the specimens, but there seems to be no doubt about its original presence. Secondary feldspar appears quite frequently on the borders of the green areas. Magnetite is present in the form of skeleton crystals.

None of the specimens exhibit any peculiarity not before described, and, owing to the extreme degree of decomposition, a more detailed description will not be attempted.

CONCLUSION.

No rocks of the character of those described in this paper have been noted before on the Pacific Coast, while none so closely related

*The writer's attention was called to this dike through the kindness of A. F. Benton, superintendent of the Eagle Ranch.

to the so-called teschenites have been found in the United States. While the original presence of nepheline has not been positively demonstrated, the phenomena shown mostly favor that supposition. The designation analcite diabase is used, although it seems to the writer that the rock really belongs among the theralites.

The most important peculiarities of the rock are the following:—

The combination of diabase granular or ophitic structure with the panidiomorphic, the augite in the main body of the Cuyamas dike being allotriomorphic, in the smaller secondary dikes partly or wholly idiomorphic.

High extinction angles in the feldspar associated with a low percentage of lime, as shown by the analysis.

The existence in the augite of a peculiar parting, which, while conforming to the position of the diallagic cleavage, yet seems distinct from it.

The beginning of alteration in the central portion of the augite crystals, resulting in silvery white, diallagic cleavage faces.

The idiomorphic forms of both feldspar and augite with reference to the analcite areas.

The presence of a large percentage of analcite under four conditions, namely: Crystallized and lining cavities in the rock; filling angular spaces between the older components; replacing the feldspars; and in the form of hexagons, idiomorphic with reference to the feldspar.

Prehnite, supposed to have been formed either in the analcite or during its derivation from some primary component.

Secondary feldspar replacing the analcite.

High percentage of soda and absence of sulphur and chlorine, pointing strongly to the presence primarily of nepheline.

Presence of secondary spherulites of an indeterminate mineral in one facies of the rock.

Geological Laboratory,

University of California, January 15, 1895.

EXPLANATION OF PLATES.

The letters in the figures refer to the following minerals: F, feldspar; P, pyroxene; O, olivine; A, analcite; SF, secondary feldspar; M, magnetite; Pr, prehnite; C, calcite; G, green matty areas.

PLATE 15.

FIGURE 1.—Main body of the Cuyamas dike. This section shows the larger undecomposed areas of analcite and the diabase granular structure. × 25.

FIGURE 2.—Large secondary dike (Cuyamas eruptive). The angular form of the analcite replacing the feldspar is characteristically illustrated; also the fibrous alteration which the analcite in the wedge-shaped areas is undergoing. × 35.

FIGURE 3.—Large secondary dike (Cuyamas eruptive). The main feature in this illustration is a basal section of the lamellar pyroxene exhibiting a fibrous center due to alteration, and the peculiar orthopinacoidal parting. × 35.

FIGURE 4.—Diallagic cleavage plate showing transverse fibration. The whole width of the crystal is not shown. The fibers are seen to terminate as a general thing on the traces of the prismatic cleavage. × 25.

FIGURE 5.—Small secondary dike (Cuyamas eruptive). One rudely hexagonal form of analcite appears in contact with a wedge-shaped area of the same mineral. × 35.

FIGURE 6.—Large secondary dike (Cuyamas eruptive). The prehnite is seen to have its form partly conditioned by the shape of the analcite area in which it occurs. × 35.

PLATE 16.

FIGURE 1.—Section from large secondary dike (Cuyamas eruptive). This section shows the prehnite crystals occupying a portion of an angular analcite area. The individuals do not seem to have grown from the feldspar inward, but to have been formed within the analcite. × 35.

FIGURE 2.—Large secondary dike (Cuyamas eruptive). The characteristic features of this section are the sharply defined areas of analcite in the feldspar, the idiomorphic prehnite, the fibrous alteration product of the analcite, and the rod-like form of the magnetite. × 35.

FIGURE 3.—Small secondary dike (Cuyamas eruptive). The important feature of this section is the presence of a large amount of secondary feldspar replacing the analcite. $\times$ 35.

FIGURE 4.—Section from a small dike (Cuyamas eruptive). Titaniferous magnetite is the characteristic feature of this section. The mineral is present in rods and more or less regular polyhedral forms. $\times$ 35.

FIGURE 5.—Oceanic eruptive showing the angular analcite areas penetrated by the short lath-shaped feldspars. $\times$ 35.

FIGURE 6.—Section showing the spherulitic facies of the Oceanic dike. The feldspars are comparatively fresh but are almost inclosed in the calcite and green matty areas. The spherulites are always associated with the secondary products. $\times$ 35.

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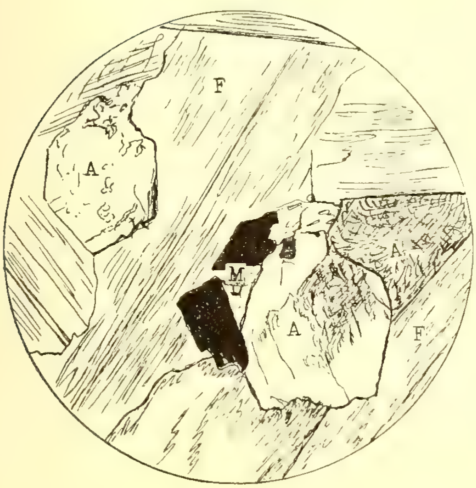

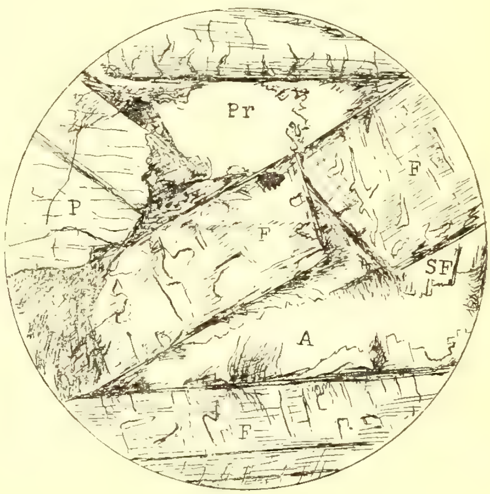

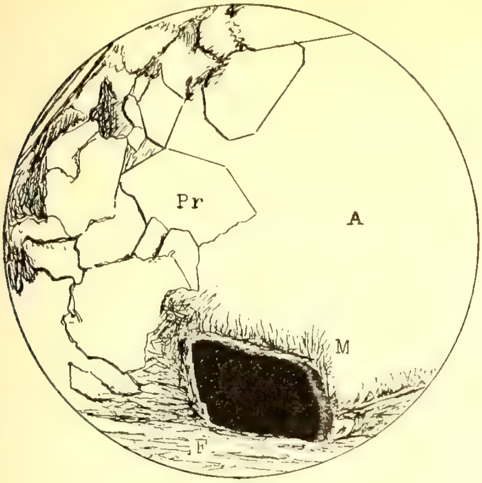

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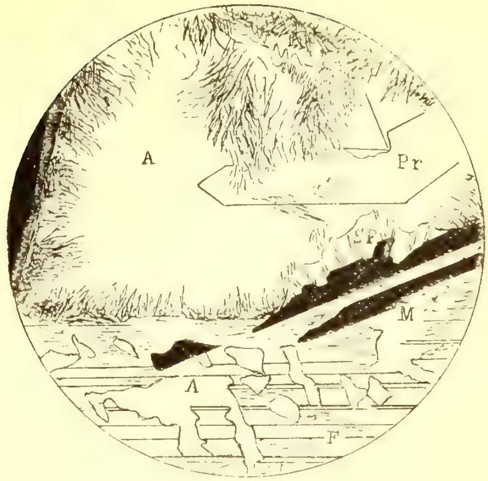

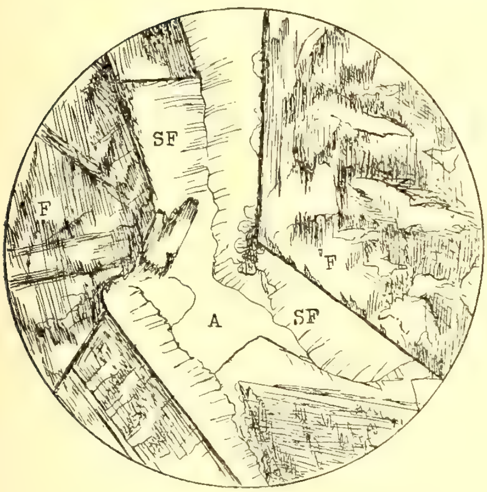

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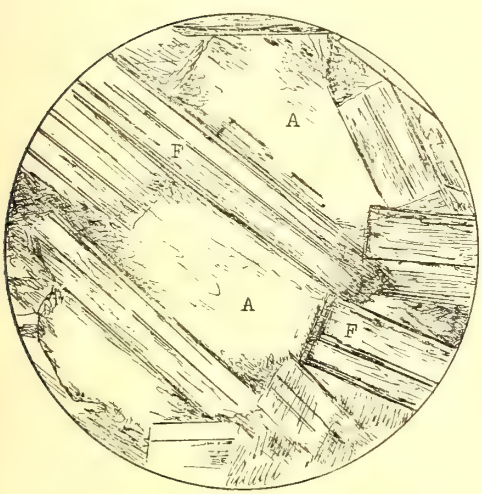

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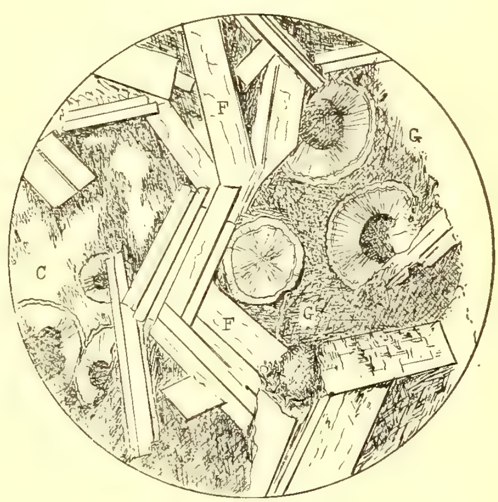

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UNIVERSITY OF CALIFORNIA
Bulletin of the Department of Geology
Vol. 1, No. 10, pp. 301-312, Pl. 17. ANDREW C. LAWSON, Editor

ON LAWSONITE

A NEW ROCK-FORMING MINERAL

FROM

THE TIBURON PENINSULA, MARIN COUNTY, CALIFORNIA*

BY

F. LESLIE RANSOME

Fellow in the University of California.

CONTENTS.

OCCURRENCE.

THE mineral for which the writer proposes the name *lawsonite*, in honor of Prof. Andrew C. Lawson, occurs as an important rock-making constituent of a rather massive outcrop of crystalline schist, which is exposed near the periphery of an extensive sheet of serpentine, on the Tiburon Peninsula, at a point about half a mile in an easterly direction from Reed Station, on the line of the San Francisco and North Pacific Railroad.

* The writer takes sincere pleasure in according to his friend, Dr. Charles Palache, the credit of a simultaneous discovery of the new mineral here described, and in acknowledging the courtesy and generosity shown by him. Dr. Palache found the mineral in his thin sections, while making a petro-

It was first noticed in the form of white crystals projecting with rough, pitted surfaces and irregular outlines from weathered blocks of the schist, the roughness of the surface and the lack of sharp crystal boundaries being due to the presence of abundant inclusions of the various other component minerals of the schist. Besides occurring as a rock constituent, lawsonite is found in much larger crystals, generally free from noticeable inclusions, embedded in a greenish-white micaceous mineral, determined as margarite, in veins traversing the schist, and also lining or filling smaller veins and cavities, as aggregates of clear colorless crystals, associated with actinolite in delicate acicular tufts.

Crystals of lawsonite are of simple habit, the most conspicuous faces being those of the prism, basal pinacoid, and brachydome. Those which project freely into cavities have the general form shown in Plate 17, Fig. 1; those embedded in the margarite, the tabular, and extended habits of Figs. 5, 6, and 7. A thin section of the massive portion of the schist shows that the mineral encloses the glaucophane and other constituents, as ice in a pond imprisons the sticks and grains at its margins. Yet it retains somewhat its idiomorphic form, as appears when the rock is subjected to weathering. The structure under the microscope is similar to the micropoikilitic structure, but differs, of course, genetically, from the structure in igneous rocks to which that term has been applied.*

CRYSTAL FORM.

Lawsonite crystallizes in the orthorhombic system. The axial ratios $a : b : c = .6652 : 1 : .7385$ were calculated from the following angles, measured on a Fuess *Universalapparat*:—

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graphical study of some of the schists from the Tiburon Peninsula, at the University of Munich, and upon accidentally learning through correspondence that the work embodied in the present paper was well under way, he immediately placed his observations unconditionally at the service of the writer. Such results as he was able to arrive at, with the very limited material at his disposal, and his suggestions, have been of great service in the preparation of this paper. It is gratifying to note that, in the matter of choosing a name, Dr. Palache and the writer are in perfect accord, as *lawsonite* was the entirely independent choice of both.

* G. H. Williams, Jour. Geol., Vol. I, No. 2, 1893.

$$m : m = 110 : 1\bar{1}0 = 67^\circ\ 16', \text{ and}$$
$$d : d = 011 : 0\bar{1}1 = 72^\circ\ 53.5'.$$

The faces of the brachydome {011} are marked by a strong striation parallel with the basal edges which renders it difficult to secure good reflections. These striations are present on the very smallest crystals that could be handled, and cause multiple and blurred signals in the goniometer. In the following table of measurements the larger variations in the observed angles must be laid to this cause, and to the difficulty of deciding just which one of a series of images is the significant one for the face. The faces of the prisms, {110} are also striated parallel with the basal edges, but less strongly than the dome faces, so that the readings are not so much interfered with.

TABLE OF ANGULAR MEASUREMENTS OF LAWSONITE.

No. of Crystal.	Angle.	No. of Readings.	Mean.	Extremes.	Calculat'd Angle.	Remarks.
1	$d : d = 011 : 0\bar{1}1$	5	72° 48.8′	72° 48′—72° 51′	....	Three signals on each face. Read middle
4	"	5	72° 53′	72° 47′—72° 56′	....	One signal rather ill-defined.
11	"	5	72° 19.8′	72° 17′—72° 22′	....	Signals faint.
12	"	2	72° 53.5′	72° 52′—72° 56′	....	Trains of signals. Read first and brightest.
13	"	3	72° 45′	72° 45 —72° 45′	....	Trains of signals. Read first and brightest.
18	"	3	72° 54.4′	72° 54′—72° 55	....	Double signals. Took mean of both.
18	"	2	72° 53.5′	72° 53′—72° 54′	....	Double signals. Read brightest.
8	$m : m = 110 : 1\bar{1}0$	5	67° 16′	67° 16′—67° 16′	....	Excellent signals.
11	$d : m = 011 : 110$	3	70° 52.6′	70° 50′—70° 55′	70° 47.4′	Signals blurred by striations.
6	$d' : m = 041 : 110$	3	58° 11.7′	58° 11′—58° 12′	58° 21.3′	Good, clear signals.
6	$d : d' = 011 : 041$	3	34° 43.3′	34° 43′—34° 44′	34° 52.2′	Good, clear signals.
10	$m : o = 110 : 001$	5	90° 0′	89° 59′—90° 3′	90° 0′	....
20	$o : d' = 001 : 041$	1	71° 15′	....	71° 18′	Angle observed by Palache.
21	$d' : m = 041 : 110$	....	58° 20′	....	58° 21.3′	Angle observed by Palache.

The mineral possesses two fairly distinct habits according as it crystallizes freely in empty clefts and cavities, or in a matrix of margarite. In the former case it has the general form shown in Plate 17, Fig. 1, less often that of Fig. 2. The small face d' of the brachydome {041} Plate 17, Fig. 3, was observed on only two small crystal fragments. Crystals possessing the habit shown in Plate 17, Figs. 1 and 2, are small, generally under 5 mm. in greatest diameter. On the other hand, such crystals as occur embedded in margarite are characterized by their greater size, and by a prevailing tabular form, the basal planes being well developed, and striated strongly, parallel with the brachy-axis. Irregularly rounded, and deeply striated brachydome faces are usually present on these larger crystals, but such simple forms as Plate 17, Fig. 7, are by no means rare. A conspicuous extension of a pair of the prism faces in a horizontal direction, as in Plate 17, Fig. 6, is so constant as to be characteristic. The size of these embedded crystals is often considerable, incomplete fragments measuring as much as 5 cm. in width across the basal plane, while the length of the perfect crystal in the direction of characteristic elongation is in some cases five or six times that dimension.

Twins are common in both classes of crystals, the twinning and composition plane being the prism. A common form of twin among the large embedded crystals is shown in Plate 17, Fig. 5 and the characteristic feather arrangement of the basal striæ is diagrammatically indicated in Fig. 4. In Plate 17, Fig. 8, is shown one of the smaller crystals, with a habit intermediate between Figs. 1 and 2, twinned according to the same law.

Lawsonite has two conspicuous cleavages, a perfect cleavage parallel with the brachypinacoid {010} and a sub-perfect cleavage parallel with the basal pinacoid {001}. Sections cut parallel with the macropinacoid show these cleavages as two sets of lines cutting each other at an angle of 90°. Those parallel with $\dot{c}$ are bolder, more abundant, and more continuous than those parallel with $\bar{b}$, which are generally fine and interrupted. There is, besides these, a third and very indistinct cleavage parallel with the prism, which has not been detected macroscopically, but can be seen in basal sections under the microscope when the light is properly adjusted, as a series

of fine, generally short and scattered, lines intersecting each other at the prism angle. This cleavage is usually much better seen in such portions of crystals as exhibit a blue pleochroism presently to be described, the lines of color in such cases running parallel with, and accentuating, the cleavage cracks. Brachypinacoidal sections also show this cleavage as short, fine lines, much scattered, and intersecting the basal cleavage at 90°.

The possibility of the mineral being monoclinic was considered, but the coincidence of the axes of elasticity with the crystallographic axes, the angle of 90° between the faces of the basal pinacoid and the prism, and the symmetrical character of the interference figure, would seem to put its orthorhombic character beyond question.

OPTICAL PROPERTIES.

The axial plane is the brachypinacoid, the acute bisectrix emerging on the basal plane. It is positive in character. The orientation of the axes of elasticity is accordingly $\mathfrak{a} = \breve{a}$, $\mathfrak{b} = \bar{b}$, $\mathfrak{c} = \acute{c}$.

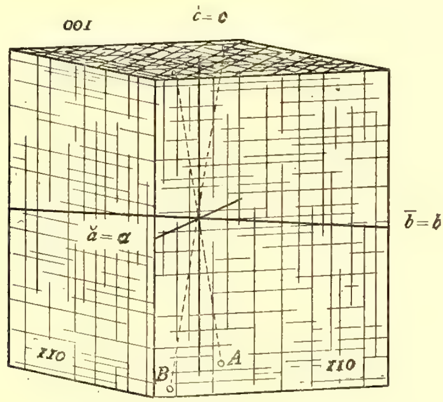

FIGURE 1. Optical scheme of lawsonite.

The acute and obtuse axial angles were measured for sodium light in cassia oil, affording the values $2\,H_a = 88°\,27'$ and $2\,H_o = 103°\,16'$, from which the value of $2\,V_a = 84°\,6'$ was calculated by the usual formula:—

$$\tan V_a = \frac{\sin H_a}{\sin H_o}$$

A value for the mean index of refraction $\beta = 1.671$ for sodium light was obtained by substitution in the formula $\beta = n \frac{\sin H_a}{\sin V_a}$, where $n = 1.6053$ the index of refraction of cassia oil.

By the usual method with specially-cut prisms, the following values were obtained for the three indices of refraction for sodium light:—

$$\alpha = 1.6650$$
$$\beta = 1.6690$$
$$\gamma = 1.6840$$

from which $\gamma - \alpha = .019$ and $\frac{\alpha + \beta + \gamma}{3} = 1.6726$.

Before suitable material was obtained from which to cut prisms, the method of the Duc de Chaulnes was employed to determine α and γ for white light. The focusing was done on a large model Nachet microscope, using an attenuated wash of carmine as a signal for the bottom of the thin plate. With the greatest care this method is subject to the possibility of serious error, but the final results obtained agree fairly well with those already given for sodium light. They are:—

$$\alpha = 1.659$$
$$\gamma = 1.685$$

A thin plate cut parallel with the axial plane, and showing between crossed nicols red of the second order, was investigated by means of the *comparateur* of Michel-Levy, and the value $\gamma - \alpha = .0207$ obtained for the measure of the double refraction in white light. This agrees as closely as could be expected with the value arrived at with the prisms for sodium light.

The dispersion of lawsonite is $\rho < v$.

In certain rather thick basal sections a strong pleochroism was observed—blue parallel with $\mathfrak{a}$ and colorless, or with a slight tinge of yellow, parallel with $\mathfrak{b}$; the absorption being $\mathfrak{a} > \mathfrak{b}$. The formula for the absorption of the mineral is $\mathfrak{a} > \mathfrak{b} = \mathfrak{c}$. The color is very unevenly distributed, however, and in some crystals may be entirely lacking. It is generally arranged in zones, or in narrow bands parallel with the prism, and therefore parallel with the prismatic cleav-

age previously described. In fact, the bands of color and this cleavage stand in very close relation, the latter being far more readily seen in such crystals or portions of crystals as show the blue pleochroism. Between crossed nicols, the pleochroic and non-pleochroic portions of the crystal are optically continuous, but show a perceptible difference in double refraction. The fact that the pleochroic zones and bands are usually found on the peripheries of the larger crystals, suggested that the pleochroism might possibly be a secondarily derived property, but this is now thought doubtful.

In thin sections of the schist, the bright polarization colors and high relief of the mineral are decidedly striking. Pleochroism can very rarely be detected in slides of the ordinary thickness.

CHEMICAL COMPOSITION.

Two chemical analyses of lawsonite have been made, and are given below in tabular form, with their molecular ratios, the derived formula, and the theoretical composition.

TABLE SHOWING ANALYSES OF LAWSONITE, AND DERIVATION OF ITS CHEMICAL FORMULA.

	I.	Molecular Ratios.	Reduced Ratios.	II.	Molecular Ratios.	Reduced Ratios.	Mean of I and II.	Molecular Ratios.	Reduced Ratios.	Theoretical composition deduced from formula.
SiO_2	38.10	.635	1.92	37.32	.622	1.95	37.71	.628	1.93	38.09
Al_2O_3	28.88	.288	.87	35.14	.341	1.07	32.43	.314	.93	32.69
Fe_2O_3	.85									
CaO	18 26	.330	1.00	17.83	.318	1.00	18.15	.324	1.00	17.77
MgO	.23									
Na_2O	.65	......	...	......	...	...	.....	...	...	....
H_2O	11.42	.634	1.92	11.21	.622	1.95	11.31	.625	1.92	11.45
Totals	98.39	.....	...	101.50	...	...	99.60	...	...	100.00

Formula: $H_4CaAl_2Si_2O_{10}$.

Number I was made by the writer in the Geological Laboratory of the University of California, on selected crystal fragments, the powder being dried at 100° C.

Number II was carried out at the University of Munich by Dr. Palache on .7 gram of material obtained by crushing and purifying small crystals.

The cause of the difference between the two analyses is not known, and it is somewhat to be regretted that time does not permit of a third analysis on the more abundant and better material now at hand. However, as is shown in the foregoing table, either of the two analyses would lead to the same formula, while the mean of the two agrees quite closely with the theoretical composition. The water is undoubtedly constitutional as the loss after raising the powdered and dried mineral gradually up to a temperature of 225° C. (the highest attainable with the apparatus at hand), and keeping it so for over an hour, was only a little over 0.1 *per cent.* The following is suggested as the probable structural formula:—

$$\begin{array}{l} (HO)_2 = Al \\ \qquad\quad\ Ca \\ (HO)_2 = Al \end{array} \begin{array}{l} >SiO_3 \\ >SiO_3 \end{array}$$

GENERAL PHYSICAL PROPERTIES AND BLOWPIPE REACTIONS.

The color of lawsonite resembles that of rather pale kyanite. Small perfectly fresh crystals are generally clear and colorless, but others, and especially the larger individuals, show a gray-blue color that is unevenly distributed through their mass, much as in kyanite. In weathering, the mineral suffers a loss of transparency and becomes gray, or mottled with grayish and milky white patches. The luster is vitreous, with a suggestion of greasiness. Its great hardness is one of its most remarkable physical properties, and is about 8 in terms of Moh's scale. It scratches topaz readily, but is in turn scratched by the latter mineral, and is apparently of the same degree of hardness. It is markedly brittle.

The specific gravity as determined by the chemical balance is 3.084. The powdered mineral as separated from the schist was found to remain suspended in Thoulet solution of 3.091 specific gravity (Palache).

Before the blowpipe the mineral fuses readily at 2.5 to 3 of Von Kobell's scale, with swelling and exfoliation to a white or light gray vesicular glass, and gelatinizes readily with hydrochloric acid after fusion. The unfused mineral is only slightly acted upon by boiling with concentrated hydrochloric acid, but is completely decomposed with the separation of gelatinous silica by heating it in a sealed tube with the same acid for eight hours, at a temperature of 140° C. Abundant water is given off in a matrass at a red heat, and does not react acid. With cobalt nitrate it gives the reaction for alumina, and affords a silica skeleton in a salt of phosphorus bead.

PLACE OF LAWSONITE IN CLASSIFICATION.

It will be seen that the new mineral falls into the second division of the subsilicates as classified by Dana in the last edition of the "System of Mineralogy," having an oxygen ratio of 2 : 3, and thereby suggesting some highly interesting analogies with the mineral carpholite. The latter has a composition of $H_4MnAl_2Si_2O_{10}$, the water being constitutional, and is regarded by Groth as a basic metasilicate. Lawsonite differs from it in composition by having the manganese replaced by calcium. Carpholite is said to crystallize in the monoclinic system, but there appears to be some doubt of this fact. The similarity in chemical composition and the probable identity of molecular structure is suggestive of the possibility of the two minerals being isomorphous, and the suggestion is strengthened somewhat by the inconsiderable difference in the prism angles, that of carpholite being 68° 33′, while the acute prism angle of lawsonite is 67° 16′.

Carpholite is optically negative, while lawsonite is positive. In regard to general habit, too, and physical properties, carpholite appears to be very different from lawsonite, but the comparison of the two is certainly interesting and suggestive.

ASSOCIATED MINERALS.

The most abundant mineral immediately associated with the lawsonite is the lustrous greenish-white micaceous mineral, in which most of the larger crystals are embedded. The folia are small, two or three millimeters in diameter, decidedly brittle, and possessing a

brilliant, somewhat pearly luster. Before the blowpipe they fuse easily, and answer well to the characters of margarite. A very little water is given off by strongly heating in a matrass. Cleavage flakes show the emergence of a negative acute bisectrix on the basal plane, with a large axial angle. This mineral occurs mainly filling veins in the schist, and inclosing crystals of lawsonite with occasional masses and crystals of pyrite.

A light-colored epidote is also very abundant in certain portions of the schist, in aggregations of small crystals, forming streaks and bands through the rock in the direction of schistosity. The color varies from pale greenish yellow to almost ash gray. The lens shows that the crystals are columnar in habit, without distinct terminations, with the faces finely striated longitudinally, and possessing a perfect cleavage in a plane parallel with the axis of elongation. Before the blowpipe, the mineral fuses with intumescence to a dark brown slag, which readily gelatinizes with acids, the solution reacting for lime, alumina, and ferric oxide. The specific gravity, determined by suspending particles in Klein's solution, is 3.326.

Cleavage flakes show a biaxial figure, of which one hyperbola only appears in the field. The plane of the optic axes is transverse to the direction of crystallographic elongation, and the optical sign is negative. This corresponds with the usual orientation of the axes in epidote. The dispersion is $\rho<v$. Cross sections (clinopinacoidal) of the crystals are generally irregular in outline, but occasionally show the hexagonal contour, and inclined extinction of epidote. Such sections give no interference figure. The cleavage is not so conspicuous in micro-sections as would be expected, and in clinopinacoidal sections is difficult to detect. Cleavage flakes, and sections which are not too thin, exhibit distinct pleochroism, $\mathfrak{c}$ pale greenish yellow, $\mathfrak{b}$ fainter yellow, and $\mathfrak{a}$ colorless or grayish, the absorption being $\mathfrak{c}>\mathfrak{b}>\mathfrak{a}$. The index of refraction is high, but the double refraction is not conspicuously strong, the colors between crossed nicols rarely mounting above those of the amphibole minerals in the same slide.

The conclusion from the foregoing description is that the mineral is an epidote poor in iron and closely approaching zoisite in composition, the poverty in iron accounting for the pale color, faint

pleochroism, low specific gravity, and comparatively weak double refraction. Although the latter is generally extremely strong in epidote, yet observations show that it may vary between wide limits,* and there seems to be no necessary reason why epidote and zoisite should not show gradations in this respect somewhat comparable with the known gradations in chemical composition.

The remaining minerals which occur with lawsonite, as constituent minerals of the schist, are actinolite, glaucophane, and abundant small red garnets in crystals up to about 3 mm. in diameter. These minerals are very variously distributed in different portions of the same mass of schist, so that the latter appears green, blue, yellowish green or red according to the local preponderance of actinolite, glaucophane, epidote, or garnet respectively. The glaucophane is not deeply colored, the color being rather unevenly distributed, and has the usual pleochroism, $\mathfrak{a}$ light yellow, $\mathfrak{b}$ light violet, and $\mathfrak{c}$ deep sky blue. The relation $\mathfrak{c} : c = 13° — 15°$ was established by means of the quartz wedge, and by reading the extinction angles of sections whose pleochroism showed them to be approximately paralled with the axial plane. The smaller angle given above, which is regarded as being nearest the true one, is twice as great as that given for typical glaucophane, but Hintze† cites similar cases of large extinction angles observed by Schluttig, Koto, and Stelzner. In this case it is probably due to some isomorphous admixture of the actinolite molecule, and is in full accord with the modern conception, that the minerals of the amphibole group form a continuous series whose members are composed of isomorphous molecules in varying proportions.

Microscopic sections also show the presence of chlorite and small, highly refracting crystals and grains of titanite. The chlorite is in most cases clearly a decomposition product of garnet.

Geological Laboratory,
University of California, May, 1895.

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* Rosenbusch. Mikroskopische Physiographie, 2d ed., p. 497.

† Handbuch der Mineralogie, p. 1258.

EXPLANATION OF PLATE 17.

$$m = \{110\}$$
$$d = \{011\}$$
$$d' = \{041\}$$
$$o = \{001\}$$
$$b = \{010\}$$

FIGURE 1.—Common habit of lawsonite when crystallizing freely in open clefts.

FIGURE 2.—Frequent habit of small crystals.

FIGURE 3.—Crystal fragment, showing occurrence of the rare brachydome face $d' = 041$.

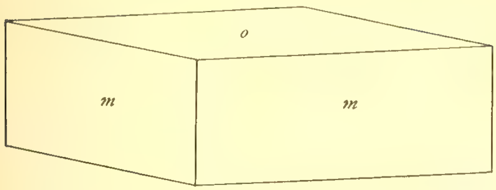
FIGURE 4.—Diagrammatic plan of twin crystal, showing striæ on basal pinacoids, positions of axial planes, and reëntrant angle.

FIGURE 5.—Twin of the habit common in larger crystals embedded in margarite. Twinning and composition plane the prism.

FIGURE 6.—Habit commonly affected by larger crystals embedded in margarite, showing characteristic direction of elongation.

FIGURE 7.—Habit of large crystals in matrix of margarite.

FIGURE 8.—Twin of the habit common in smaller crystals.



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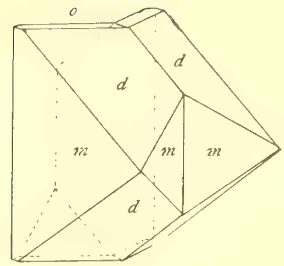

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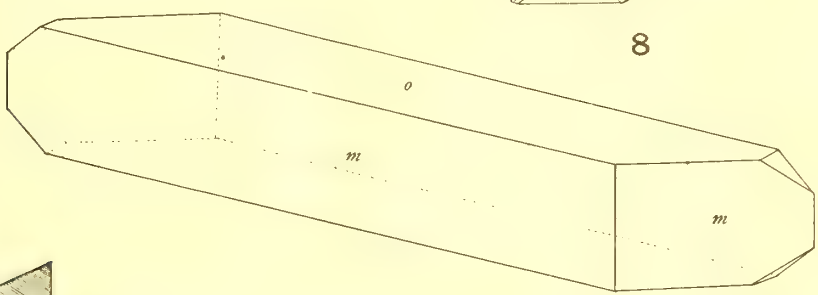

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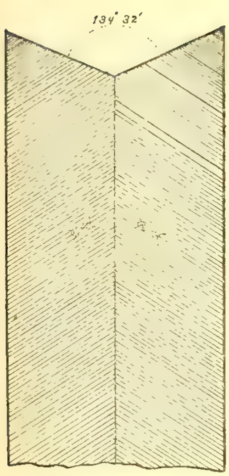

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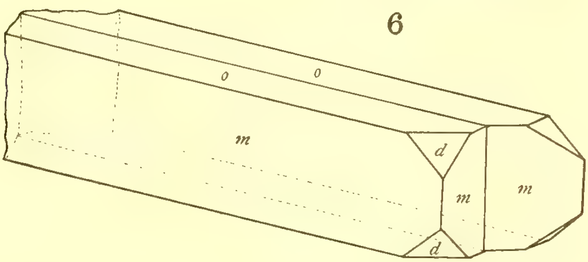

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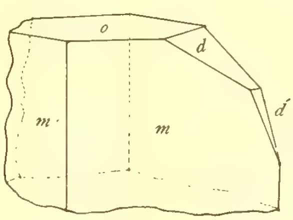

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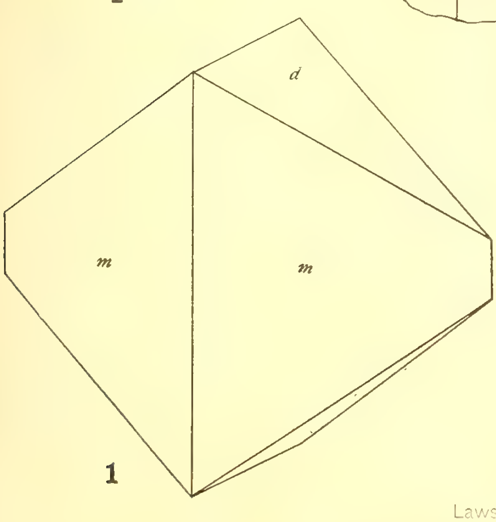

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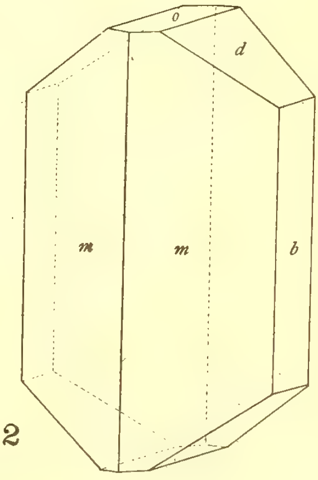

2

Lawsonite

UNIVERSITY OF CALIFORNIA
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Vol. 1, No. 11, pp. 313-336. ANDREW C. LAWSON, Editor

CRITICAL PERIODS

IN

THE HISTORY OF THE EARTH.*

BY

JOSEPH LE CONTE.

CONTENTS.

* The following article, in a more condensed form, opened the discussio by the Congress of Geologists, at Chicago, August, 1893, on the question, "Are there any natural divisions of the geological record which are of world-wide extent?"

INTRODUCTION.

Inapplicability of European Standards.—Geology was first studied in Europe; and the divisions and subdivisions of the rocks and of time were based on the great unconformities of the rock-system and the great changes of the life-system observed there. When investigations extended to other countries, naturally, similar divisions were looked for and apparently found. Closer study, however, soon showed that the correspondence was not complete for America, and seemed to fail entirely for India, Australia, and Africa. The tendency, therefore, in recent years has been to seriously doubt whether there are *any* divisions which apply to *all* places; whether we should not give up trying to write a general history of the whole earth; whether the history of each continent must not be studied for itself. There seems to be a real danger of opinion going too far in this direction. It has been proposed, therefore, that this question be discussed by this Congress of Geologists.

It will be admitted that for a comprehensive view of any subject some knowledge of the history of thought on that subject is necessary. First, then, a few words on this history.

Early Views.—In the early part of the present century, events of geological history were supposed to be not only removed from direct observation, but so different from anything now occurring that exact reasoning on them based on observation of causes now in operation seemed hopeless. The construction of the history of the earth by interpretations of its structure seemed, therefore, a legitimate field for the exercise of the scientific imagination. Hence it was that unconformities of strata associated with sweeping and apparently sudden changes of life-forms were naturally attributed to violent and destructive convulsions of the earth's crust and wholesale exterminations and recreations of all life-forms. Geological history was a succession of catastrophes, each inaugurating a new era, which remained substantially unchanged until another catastrophe. This view was in full accord with the then prevalent doctrine of the supernatural origin of new organic forms and the permanency of specific types, and regarded as a strong confirmation of the latter. Geology was not yet a science in the proper sense of

that term. It was a field for the exercise of imagination rather than inductive reasoning.

The basis of modern geology, structural and dynamical, was undoubtedly laid by Lyell in the idea that the study of "causes now in operation" producing structure under our eyes is the only sound basis of reasoning from structure to history; and similarly, the basis of palæontology was laid by Darwin in the "theory of evolution or origin of organic forms by descent with modifications." But by a natural revulsion from the previous catastrophism, these new views, especially before they were modified by the doctrine of evolution, were undoubtedly pushed much too far, and became embodied in the opposite extreme doctrine of uniformitarianism. According to this view, things have gone on from the beginning at a uniform rate, much as they are going on now—changes of relation of sea and land, now here, now there, now in one direction, now in the other—oscillatory and compensatory, without detectable progress in any direction and without assignable goal. The view was conceived in the spirit of the physicist rather than of the biologist, and may be called physical rather than geological. The many changes in the history of the earth were *compensatory* not progressive. The underlying idea was *stability* rather than evolution. And even Darwinian evolution, when accepted, was supposed to imply evolution at uniform rate—*uniformitarian evolution.*

Now, however, opinions are settling down into a view which is a substantial reconciliation of these two extremes, viz.: that of gradual evolution both of the earth and of organic forms, but *not at uniform rate*. According to this, as I believe, truer view, in the gradual evolution of the earth and its inhabitants as a whole, there have been periods of *comparative quiet*, during which forces of change were gathering strength, but resisted by an opposite conservative force (crust-rigidity in the case of earth forms, inherited character or type-rigidity in the case of organic forms), and periods of *revolution*, during which resistance gives way, and conspicuous changes take place with comparative rapidity. Changes indeed go on all the time, but more rapidly at these times.

I shall not stop to illustrate and show how all evolution, just because it is under the influence of two opposite forces or principles,

—the one progressive and the other conservative, the one tending to changes, the other to stability,—is more or less subject to this law of cyclical movement. Laws and forces, indeed, are uniform, but phenomena everywhere and in every department are more or less paroxysmal or catastrophic; though not catastrophic in the old sense of being not subject to law.

Thus, the fundamental idea underlying geological reasoning was first *catastrophism*, then *uniformitarianism*, and now *evolutionism*. But evolution moves not at uniform rate, but by cycles as explained above.

How Far May Divisions Be Made General.—Now the important practical question in regard to these revolutionary changes—which all must admit for special localities—is: How far are they, or at least some of them, general? How far may they, or any of them, be used to determine the divisions and subdivisions of geological history of the whole earth? This, as I understand it is the question under discussion.

Until recently, perhaps under the still lingering influence of the old catastrophism, the prevalent idea was that *all* these great changes marked by unconformity and concurrent changes in organic forms were general. Under this idea European standards of classification have been used as a procrustean bed to which all others must conform, even in detail. This has been found difficult for our American rocks, and impossible for those of India, Australia, and South Africa. Therefore the tendency of the present time among most advanced geologists is strongly toward a rejection of all general divisions—to hold that all such changes are local and therefore all divisions of record and of time, both primary and secondary, and therefore all classifications must also be local. But again the danger is that by revulsion this tendency also may go too far. It is against this that I would raise a note of warning.

If, indeed, the earth has developed *as a whole*, as evolutionism would seem to require, then we ought to *expect* that amid many smaller and more local changes there *must* have been some greatest revolutions which have in some way either directly or indirectly affected the whole earth, and which therefore may be used to form the basis of the primary divisions of time. In the gradual changes

of the earth as a whole, whether by secular cooling and contraction or by slowing down of rotation by tidal friction or otherwise, there must have been, from time to time, readjustments of the crust affecting the whole earth.

CRITICAL PERIODS.

The thesis which I wish to maintain, then, is, that there have been what I have elsewhere called "critical periods" in the history of the earth,* *i. e.*, periods of very general readjustments of the crust of the earth, and therefore of widespread changes in physical geography, so great and so general as to affect profoundly and widely the climates of the earth; that these physical changes in their turn gave rise to still more marked changes in organic forms; and finally that all these changes together form a rational basis for the primary divisions of time.

These great and comparatively rapid changes in *organic forms* are produced in the following ways: 1. The changes in physical geography open gateways and permit migrations in many directions. 2. The changes in climate, besides their direct effect on organism, *compel* migrations mainly north and south. 3. These migrations in their turn precipitate different faunas and floras upon one another, producing severe struggles between invaders and natives, and therefore the destruction of many forms of both, and large modification of the survivors. 4. The foreign invasion compels many natives in their turn to migrate, and so the wave of invasion, of severer struggle, and of consequent changes is propagated as far as physical conditions will allow migration. The effect of all this must be a more rapid rate of evolution of organic forms, as the result (*a*) of a new environment, and (*b*) of a severer struggle for life. The more rapid rate of evolution, and especially *new opportunities*, give rise to *higher dominant classes*. These higher dominant classes again in their turn determine changes in lower forms, especially their immediate rivals, and these changes are again propagated downward through the whole organic kingdom and compel a new adjustment of the whole on a different basis.

The great theater of physical changes, of extensive migrations,

* Am. Jour., vol. 14, p. 22, 1877.

and of severe struggle, and therefore of rapid evolution, especially of higher forms, and therefore also the place of *first appearance of dominant classes* has undoubtedly been what Huxley calls *Arctogæa*, *i. e.*, North America, and Eurasia north of the Himalayas and Sahara, or all the northern hemisphere north of Central America, Sahara, and the Himalayas. This, the greatest body of contiguous or continuous land, has in later geological times been sometimes united, sometimes divided. It has been subject to the greatest changes, the widest migrations, the severest conflicts, and therefore the most rapid evolution of dominant forms. But these dominant forms have from time to time, as opportunity offered, invaded more southern lands, and always as conquerors.

Signs of Critical Periods.—These greatest revolutions are marked in the rocks (1) by widespread unconformities, and therefore by a loss of record which is greater in proportion as the unconformity is more general. But since unconformity always means eroded land surface, widespread unconformity must mean greatly enlarged continents, or a continental period between two comparatively oceanic periods. (2) They are marked by great, very general, and apparently sudden changes in organic forms, affecting not only species, but also genera, families, and orders. (3) By the introduction of new and higher dominant classes. (4) By the birth of great mountain ranges. Of these characteristic signs the most general and important is the change in organic forms. This is, therefore, the most important means of determining the *primary* divisions of time, but the other signs are usually concurrent and are therefore confirmatory. The *secondary* divisions are based on less general changes, and are therefore themselves more local in their application.

It must not be imagined, however, that these great revolutions of the earth's crust are catastrophic, in the sense of being instantaneous. On the contrary, although they were periods of exceptional commotion, they continued probably hundreds of thousands of years. Nor were they simultaneous everywhere in any mathematical sense. On the contrary, the changes were doubtless propagated from place to place until readjustment was complete. So, also, and still more certainly, the changes in organic forms were propagated

from place to place by migrations and conflicts as already explained. Therefore the line of delimitation between the primary divisions will not be drawn at exactly the same horizon in all places.

I wish now to show that there have been several such critical periods, or periods of very great changes affecting the whole earth, and that they form a rational basis for primary divisions of the geological record, applicable to all parts of the earth. I begin with the *last;* not because it is the greatest, for it is indeed in many respects the least, but because it is the nearest to us and therefore the clearest, and on this account may be expected to throw light upon the real nature of such periods. I shall call such periods critical periods or revolutions.

I. THE GLACIAL REVOLUTION.

The Drift or Quaternary or Glacial Period, or Ice Age, I am convinced constitutes one of these critical periods and the last. I have called it the Glacial Revolution.

The cause of the glacial climate we shall not discuss. Whatever it be, whether geographical or astronomical, or both, it is certain that it was attended with great and widespread oscillations of the earth's crust by elevation and depressions in all high latitude regions. The greatness of these oscillations we are only beginning to understand. The North American continent, for example, was certainly raised at least three thousand feet and probably much more. The continent was enlarged until the shore line advanced to and even beyond the submerged continental margin. In Europe the elevation was equally great. It is probable also that the southern hemisphere was similarly affected nearly if not absolutely simultaneously. From the distribution of organic forms in the southern hemisphere there seems much reason to believe that the Antarctic continent was elevated and enlarged until it connected with and connected together the point of South America, South Africa, Australia, and New Zealand. The effect of these great changes in physical geography would be to produce corresponding extreme changes in climate and wide migrations of organic forms, partly permitted by changes in physical geography and partly enforced by changes of climate. These migrations extended not only

throughout Arctogæa, but also southward into all the southern continents, except Australia. Madagascar, and the coast islands of California seem also to have escaped.* These great changes, as already explained, determined a more rapid evolution of organic forms, especially among the higher animals.

This, then, I believe ought to be regarded as a critical period, and therefore a dividing line between two primary divisions of the earth's history, viz.: the Cenozoic and the Present. The Present, therefore, contrary to the view of most geologists, I regard, and insist on it, as a *primary* division of time, and the glacial period as the transition or critical or revolutionary period separating it from another primary division, the Cenozoic.

I so regard it because it bears all the *marks* of a primary division of time. 1. There is widespread unconformity of present sediments on all previous strata. This is seen in old river beds, in the deposits of great glacial lakes, and in all the sea margin deposits as far as the submerged continental margin. In addition to this, if we admit the great enlargement of the Antarctic continent already mentioned, the unconformity extends over the whole Antarctic Ocean bottom. If to all this we add the unconformity of the drift itself on its eroded bed rock, surely the wideness of this unconformity is scarcely inferior to that of any other critical period. Very much of this is now concealed beneath the ocean by subsequent subsidence of land. 2. There are here also very great and rapid changes in organic forms, especially among mammals. The change in the mammalian species since the Tertiary, *i. e.*, during the Glacial Revolution, is complete. In lower forms the change as yet is less complete than in previous critical periods. I said, *as yet*, because it is still going on rapidly. 3. There is here the introduction of a new and higher dominant type, man. I must stop a moment to enlarge on this.

Effect of New Dominant Types.—New dominant types, as already shown, are always an important factor, increasing, continuing, and completing the changes commenced by other factors of evolution. This is well illustrated by the rapid disappearance of the great Meso-

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* Am. Jour., vol. 34, p. 457, 1887.

zoic reptiles on the appearance of the Tertiary mammals, and of the great Palæozoic ganoids on the appearance of the Mesozoic reptiles. But in the case of the appearance of man, this effect was far greater than in any other. The changes of life-forms produced during the glacial period in the manner already explained have been continued and increased by man. The whole fauna and flora of the earth are now being changed by his agency and readjusted to his wants, and the change will be completed only when the whole earth is occupied by civilized man. Evidently, then, there is now going on under our eyes and by human agency, a change in organic forms, more complete and more rapid than has ever before taken place in the whole history of the earth. Shall we ignore it because we are in the midst of it, or because we are ourselves the main agent in bringing it about? Must not man be accounted among the agencies of nature?

4. Among the characteristics of critical periods we mentioned also the birth of great mountain ranges. Have we any such born at this time?—I think we have.

On account, I suppose, of the increasing rigidity of the earth's crust, the great movements of this time were mainly epeirogenic not orogenic. Mountains of the usual type, *i. e.*, by strata-crushing, were not formed unless we make an exception in case of plications of Pliocene strata in the Coast Ranges of California, mentioned by Lawson.* But on the western margin of the American continent, mountains of the monoclinal type, *i. e.*, by *block-tilting*, were formed on a grand scale. Examples of these are found in the Basin-ranges, in the Sierra Nevada and Wahsatch (which border the basin on either side), and in Alaska, as shown by Russell, in Mt. St. Elias Range. All these mountains had been already formed at a previous time as mountains of the usual type, but at the end of the Tertiary or beginning of the Quaternary, they were rejuvenated and their present forms and heights given as mountains of the monoclinal type.

It is almost impossible to overstate the greatness of the changes which took place during this wonderful period. Besides the eleva-

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* This BULLETIN, Vol. I, Nos. 4 and 8.

tion of the American continent from 3,000 to 5,000 feet, and its extension to the border of the now submerged continental margin, and the formation of mountain ranges of monoclinal type; besides the broad connection with Asia by the Behring region, and with South America by the Antillean region; besides the enormous climatic changes and its resulting ice sheet, we must add also great extensions of lakes so as to form inland fresh water seas in the Canadian Lake region and in the Basin region. We must add also the greatly increased elevation of the plateau region and the cutting of the inner gorge of the Grand Cañon, and the cutting of all the grand gorges which trench the flanks of the Sierra Nevada.

Equally great epeirogenic movements are known to have occurred in Europe, Africa, and South America, but it would carry us too far to dwell on these.

Psychozoic Era.—I repeat, then, that the present must be regarded as a primary division of time, *i. e.*, an *Era.* If so, it deserves a distinctive name as such. I have called it the Psychozoic Era. If anyone can suggest a better name, I shall willingly adopt it.

I have treated the Quaternary or glacial period as a transition or critical period between two great eras, the Cenozoic and the Psychozoic. To which of these it ought to be united is a question of less importance. Critical periods are usually largely lost intervals. This one, partly because the oscillations were perhaps not so great, but mainly because it is so recent, has been recovered. The lost records of other critical periods have also been partly recovered, and more will be recovered hereafter. In these former critical periods the recovered record has usually been united with the *previous* era. The new era commences only when the new forms are well established. Thus the Permian is united with the Palæozoic and the Laramie with the Cretaceous. Therefore it is proper that the Quaternary or glacial period should be united with the Cenozoic. But unfortunately it has been usually supposed that this carries with it also the Present as a mere epoch of the Quaternary. Because the record of this interval has been entirely recovered; because the change in this case is seen to be gradual instead of apparently sudden, as is often the case in other critical periods; and finally because it is not yet completed but still going on under our eyes, most geol-

ogists do not recognize the greatness of the change. If it were farther away, already completed, and the records of the gradual process lost, it would be recognized at once. As the great mass of a mountain range cannot be seen when we are amongst its peaks, so being in the midst of this great change, and seeing it so close at hand we fail to catch the true perspective and recognize its greatness.

If, then, the Psychozoic be acknowledged as an Era, the Quaternary ought to be united with the Cenozoic rather than the Psychozoic. It is true it may be objected, as has been done by Upham,* that *man appeared in the Quaternary.* The answer to this is, that he had not yet established his supremacy, but still contended doubtfully with the great mammals of that time. This is in full accord with the cases of other eras. Reptiles appeared first in the Permian, but the age of reptiles commenced only with the Mesozoic. Mammals were introduced first in the Mesozoic, but the age of mammals commenced only with the Cenozoic. So man was introduced in the Quaternary and possibly even in the Tertiary, but the Age of Man commences only with the Psychozoic. The changes must not only commence but be substantially *completed* and a new order of adjustment established, before a new era begins.

This critical period, as the last, the nearest to us, and therefore the clearest, *may be taken as the type.* The attentive study of this one ought to throw abundant light on the true nature of critical periods in general. It is, however, the shortest in lapse of time. It is, also, probably the least so far as physical changes are concerned, and therefore also so far as changes of life-forms produced by physical changes, are concerned. But it is by far the greatest of all so far as concerns the effect of its dominant type in determining changes of all kinds.

We have taken this one as the type and dwelt upon it, because its significance is not generally recognized. The other examples are well known and their importance recognized. They may be easily explained in the light of this one and therefore may be quickly dispatched, especially as I have already treated them fully in the article previously referred to.

* Am. Nat., 28, 980, 1894.

II. THE POST-CRETACEOUS OR ROCKY-MOUNTAIN REVOLUTION.

The next in order, going backward, is that which separates the Mesozoic from the Cenozoic, or more definitely, the Cretaceous from the Eocene. The physical changes which occurred at this time in America, are, (1) the *unification* of the American continent by the final abolition of the great interior Cretaceous sea which previously divided the continent into two parts, and (2) the formation of the Colorado, the Uinta, and Wahsatch Mountains. In America, this may therefore be called the Rocky Mountain Revolution. Similar, and even greater movements seem to have occurred in other continents, for the unconformities are even greater there than in America.

Here again we have widespread crust oscillations accompanied by (1) great changes in physical geography, shown by very general, almost universal, unconformity of Tertiary on Cretaceous or on still lower rocks, in every part of the world. Only in a few places on the American continent, *e. g.*, in the plateau region and in California, is the stratification doubtfully continuous. (2) By rapid changes of life-forms even where the sedimentation is continuous. (3) The introduction of a new and higher dominant class, the Eutheria. (4) Wide migrations partly permitted by changes in physical geography, and partly enforced by changes of climate; and consequent great and rapid changes in organic forms, partly by pressure of a new environment, partly by mingling of faunas and floras, and partly by necessary readjustment to a new and higher dominant class.

The apparent suddenness of the change in organic forms—for example, in this case the appearance of Eutheria—is the result partly of loss of record (unconformity of strata), but mainly, I believe, of migrations (unconformity of faunas and floras). This suddenness, however, has in this case been probably exaggerated. Until recently, after the Jurassic Metatheria, no mammals were known until the Tertiary. But then without apparent transition an entirely different and higher type suddenly appeared in great numbers. The discovery by Marsh of mammals in the uppermost Cretaceous was therefore hailed as probably filling the great gap. But according to Marsh these are all of pure Mesozoic types, and there-

fore bring us no nearer the origin of the Tertiary mammals than before. Osborn, however, finds them distinctly transitional, *i. e.*, as nearly allied to the Puerco, lowest Tertiary, Eutheria, as they are to the Jurassic Metatheria.

In this revolution the geographical changes were probably much greater than in the glacial, although far less known. The life-changes were also much greater, except for the effect of man in the latter. As the drift represents deposits during the Glacial, so the Laramie those during this revolution. The Cretaceous proper was before, the Tertiary after, the Laramie *during* the revolution. The time occupied in the change and represented by the Laramie formation was very much longer. The break in the record was much greater and more general, but yet not universal as witness the continuity of strata in some parts of the west. Undoubtedly Eutheria or true mammals appeared first in Arctogæa, as this was the great field of extensive migrations and the battle ground of species, and therefore the place of most rapid evolution. From thence they spread by migration everywhere except isolated Australia.

These two periods, viz., the *post-Cretaceous* and the *post-Tertiary*, were undoubtedly periods of very great and widespread changes, probably effecting nearly, if not quite, the whole surface of the earth. Now, have we anything at all comparable to these in the intervening Tertiary?—Surely not. They are therefore properly called *revolutionary* periods, and should be made the lines of demarkation separating primary divisions of time.

Among the changes of climate, perhaps of many kinds which took place in the last or *glacial* revolution, we find the most conspicuous is that of extreme cold. Do we find any such in the post-Cretaceous revolution? According to Dana there are some evidences of a *cooler* climate than before or after. But the evidence is not clear, nor is it probable that the lowering of temperature was extreme.

III. THE POST-PALÆOZOIC OR APPALACHIAN REVOLUTION.

Going still back the next, and perhaps the most conspicuous of all, is that which separates the Palæozoic from the Mesozoic. If we call the *Permian* a transition or critical period, corresponding to

the *Laramie* and the *Glacial*, there is good reason to believe that it was of much longer duration than either of the others. The readjustments of the earth's crust were much greater and it was much longer time before the equilibrium was settled and the organic kingdom again in a prosperous condition. The unconformity in this case was still greater and more general, and the loss of record, therefore, greater. The change in life-forms was simply enormous, the greatest that has ever occurred in the history of the earth. In Arctogæa the unconformity is almost universal, though not everywhere on exactly the same horizon. In the Southern Hemisphere, including India, Australia, and South Africa, there is little or no unconformity, but none the less are the changes of life-forms great and rapid at this time, doubtless by change of climate and by migrations of conquering Mesozoic forms from elsewhere.

The mountain-monument of this great period of change, in America, is the Appalachian Range. It is therefore called by Dana the Appalachian Revolution. But everywhere it was a period of great changes, and many other mountains originated at this time.

Observe again that the time intervening between this and the post-Cretaceous or Rocky Mountain Revolution, viz., the Mesozoic, was a time of remarkable quiet and wonderful prosperity of the organic kingdom. It is true that here in America and elsewhere there were important changes in physical geography and some mountain making at the end of the Jurassic, but these changes were far less general and therefore far less potent in determining changes in the organic kingdom.

Among the causes of change in organic forms, one of the most potent is oscillation of temperature. Now the most decided evidences of glaciation known in any period except the glacial, are found in the Permian, and that, too, in many widely-separated regions. This is especially true of Australia and South Africa, where the glaciation seems to have been severe and undoubtedly connected with the great elevation and enlargement of the Antarctic continent, already spoken of. We have in these facts a probable key to the origin of the great reptiles of the Mesozoic. May they not have come by migration from the Southern Hemisphere, which seems to have been the home (Karoo beds) of the earliest and most

generalized forms of reptiles, viz., the Theriodonts? It is not probable, however, that there was at this time any such general ice-sheeted condition of middle latitude regions as existed in the glacial period. But that there were severe and general oscillations of temperature there is little doubt.

IV. THE PRE-CAMBRIAN REVOLUTION.

Last in the order of mention, but first in the order of time, and, so far as physical changes are concerned, by far the greatest of all, is the *pre-Cambrian revolution*. The Paleozoic era, especially in America, was a time of quiet, of prosperity, and steady evolution. Changes occurred, indeed, during this time, many and great, but not to be compared either in greatness or in wideness to those preceding and succeeding. The revolution at the end, viz., the Appalachian was more conspicuous than that before, only because of the great abundance of life both before and after, and the completeness of the change between. It was therefore equally conspicuous in the life-system and the rock-system. The pre-Cambrian revolution was even greater in the rock-system (for judging by the universal unconformity it was literally a continental period between two oceanic periods), but there can hardly be said to have been any previous life system with which to contrast that of the Palæozoic. It is not improbable that farther study will reveal other important divisions, but the meagerness of our knowledge makes it unnecessary to dwell farther on this.

Are there any mountain ranges connected with this revolution? —Probably there are. The Laurentide Mountains, of Canada, and the Adirondacks, of New York, are probably examples, but most of such have been swept clean away by erosion and only their fossil bones left in the form of complexly-folded structure of pre-Cambrian rocks.

These four revolutions, then, I would insist on as marking primary divisions of time. Important movements occur between these, but far less general, and therefore far less effective in changing organic forms, and therefore should form the basis of *subordinate* divisions only. *Three* of these great revolutionary periods are generally recognized, but the fourth and last, viz., the *glacial*, is not

usually recognized as such. On the contrary, I regard it as the type, as the best proof of the fact of critical periods, and as throwing abundant light on the true character of such periods, and especially on the causes of the enormous changes in organic forms, during such times. These four, then, are the great landmarks of time. All other and lesser divisions are more or less local. If we recognize the primary divisions, then these become the fixed points for correlating the lesser divisions, as is now being so successfully done by the U. S. G. S. in its admirable series of correlation papers.

PROGRESSIVE CHANGES IN SUCCESSIVE CRITICAL PERIODS.

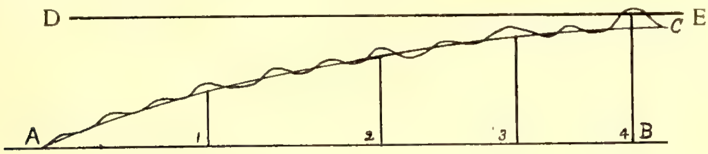
It may be interesting to compare the successive critical periods with one another and show in *them* also *progressive* change or *evolution.*

1. Critical periods have gradually become shorter and shorter, the changes in physical geography less and less, and therefore the changes in organic forms, in so far as they are connected with these latter, also less and less. The shortest in duration, the least in geographical changes and the least complete and sweeping in changes of organic forms is the last. It is for this reason that it is not usually recognized. But this is exactly what we ought to expect from a comprehensive survey of the whole history of the earth, *i. e.*, from the point of view of evolution.

2. But on the other hand the effect of the introduction of new dominant types in producing changes in the whole organic kingdom has been steadily *increasing.* It was great in the introduction of the great reptiles, much greater in the introduction of the Eutheria, and by far the greatest of all in the introduction of man. Thus this last critical period is not a whit behind the others in importance, and therefore deserves no less than the others to be used as separating Primary Divisions of Time.

3. The oscillations of *temperature* characteristic of critical periods have probably gradually *increased* with the course of time. Local oscillations of temperature doubtless occurred frequently. At critical periods they were both greater and more general, but I suppose that glacial conditions at sea level in middle latitude regions was reached but once, viz., in the last. This is illustrated by the

accompanying figure, in which the abscissa A B represents the course of time, the ordinates the degrees of cold, and the height of the line D E represents such a degree of cold as is necessary to produce glacial conditions at sea level in middle latitudes. The



gradual rise of the line of cold, A C, represents the gradual cooling of the earth surface, whether by secular cooling or by decrease of carbonic acid and water in the atmosphere, or by both; and the waving of the line, the oscillations of temperature. The numerals 1, 2, 3, 4, are the times of revolution or critical periods marked by greater and more general oscillations, the smaller intervening waves being the more local oscillations. It is seen that only once, *i. e.*, during the last critical period, partly by increased general refrigeration, but mainly by a concurrence of causes, geographical and astronomical, true glacial conditions (represented by the line D E) were reached.

Critical periods, as already said, are of long duration and changes during such times are not simultaneous everywhere, but rather propagated from place to place. This is especially true of the changes in organic forms. These are propagated by a wave of migration which may extend far beyond the limits of the physical changes. Therefore the time of greatest change in organic forms may not be exactly synchronous everywhere. This fact gives sufficient room for the application of Homotaxis.

GENERAL FORMAL LAWS OF THE EVOLUTION OF THE ORGANIC KINGDOM.

We may now profitably sum up the general formal laws, or the general process, of the evolution of organic forms; for it is these more than aught else which determine the divisions of time, both primary and secondary.

General Advance by all Factors.—Let us imagine then, first, a

steady advance of the whole organic kingdom, everywhere and all along the line, under the operation of all the factors of evolution known and unknown, whatever these may be. If this were all, there would be successive *geological*, but no simultaneous *geographical*, faunas and floras. Organic forms would change in *time* but not differentiate in *space*. The determination of synchronism or of a geological horizon in different continents, would be easy because the identity of fossil forms of the same time in all parts of the earth would be absolute. A chronology of the earth would be easy to construct, because it would be the same everywhere. There would be everywhere but reprints of the same history. This is one extreme, but we know it is far from the real truth.

Origin and Increase of Geographical Diversity.—Different conditions in different places isolated from one another by barriers, physical, climatic, or both, and therefore without mixture of species by migration, give rise to different *rates* or *directions* of advance and therefore to *divergence* of geographical faunas and floras, which increase *without limit with time*. If *this* were all, there would long ere this have come about an *extreme diversity* of geographical faunas and floras; more extreme than any we now know. Indeed, so extreme that determination of synchronism of strata of different places by comparison of their fossils would be impossible. The geological history of each country must be studied for itself. There could be no general history of the earth and no general classification of the strata. This is the other extreme; but neither is this true.

Critical Periods Diminish Geographical Diversities.—But from time to time, at great intervals, there occur critical periods, *i. e.*, periods of great and widespread changes in physical geography, and therefore of climate, and therefore, also, in organic forms. These latter changes, as already explained, are determined partly by the pressure of a changed environment and partly by wide migrations—both permitted by removal of barriers and enforced by changes of climate—and the consequent mingling of faunas and floras previously separated, the severer struggle consequent thereon and more rapid rate of evolutionary changes. In connection with the new conditions, the severer struggle and more rapid evolution, there would arise at these times new and higher dominant types which

would still farther increase the change of organic forms by compelling a new adjustment of the whole organic kingdom. This is especially true of the effect of the appearance of man. The effect of all this would be to *hasten the steps of evolution* and *increase organic diversity*, but to *diminish geographical diversity.* These critical periods form the lines which delimit the primary divisions of history.

Rë-isolation.—Lastly there come rë-isolations of the mixed faunas and floras in their new positions; and geographical diversity again commences and continues to increase without limit in proportion to the time and degree of isolation.

Thus in the history of the earth there have been alternate periods of minglings and rë-isolations of faunas and floras; of effacement, and reëstablishment of geographical diversity. Every period of mingling has increased the force and quickened the rate of evolution and the diversity of organic forms.

As already shown, the glacial period is the last of these critical periods of migrations, minglings, struggles, and the present a period of rë-isolations and increasing geographical diversity (except in so far as interfered with by man) and of readjustment of the whole organic kingdom to the dominant type, man. Therefore the glacial period furnishes the key to the present geographical distribution of species, especially among the higher forms, and conversely the present geographical distribution of species furnishes a key to the changes in physical geography and the directions of migrations of species during that critical period.

SUDDENNESS OF CHANGES AND RARITY OF TRANSITIONAL FORMS.

There are many important questions suggested by the foregoing discussion. Chief among these and the only one I now touch, is the question of the *cause of the suddenness* of the appearance of new organic forms, and the extreme rarity of transitional forms or connecting links at all times, but especially during the critical periods.

As already said, the greatest and most rapid of all these changes is that which occurred in the critical period between the Palæozoic and Mesozoic. We may therefore take this as the type in this regard. It is almost impossible to exaggerate the greatness of the

change which took place here. Passing from the one era to the other is like going from one world into another. How shall we account for this great and apparently sudden change?

Lost Records.—The first and greatest cause, especially of the *suddenness*, is, of course, the *loss of record*. Certain leaves of the book of time are missing, and when we come to read again, the subject matter of the volume is greatly changed. This accounts for the absolute *suddenness* in some cases, but not for the *greatness* of the change, for this is out of all proportion to the lost interval of time. Therefore we must admit farther:

Rapid Steps in Evolution.—The steps of evolution were exceptionally rapid at this time. We have already given the causes of this more rapid movement. But even when the record is recovered, as for example, in India, Australia, etc., we find still that connecting links between successive forms are rare—links are usually missing. Therefore it is necessary to remember also that there are

Few Generations Represented.—The changes being more than usually rapid, the number of generations necessary to accomplish a certain amount of change, *i. e.*, to transform one species into another, were comparatively few. Therefore when we remember that fossils are but a small fraction of the actual number of individuals living at any time, the likelihood of finding transitional forms is diminished to that extent. Again, add to this the fact of

Few Individuals in Each Generation.—The conditions must have been unfavorable to fullness of life. The changes in the *environment* were rapid, and therefore adaptation of organisms to the environment must have been imperfect. In a word, critical periods are *hard times*. But hard times react and produce less reproductive fertility, and therefore fewer individuals in each generation. Therefore critical periods are characterized by poverty of fossils, even when the record is recovered.*

*It would carry me too far to dwell on the causes of infertility in critical periods, but it may be well here to recall Brooks' idea that, in the female, heredity and fixedness, and in the male, the tendency to variation, predominates. Therefore the female is the conservative, and the male the progressive element in evolution. Now in many lower animals abundant food and prosperous times tend to excess of females and therefore abundance of individuals, while hard times tends to excess of males and therefore to fewness of offspring but to rapid variations of forms.

Migrations and Consequent Unconformity of Faunas.—Last of all among the causes, we must not forget migrations, which, aside from the rapid changes produced by severer struggles, produce also *unconformity of faunas and floras*, and therefore an *appearance of suddenness* of change in any one place. Such changes of species by migrations, although most conspicuous in critical periods, take place locally even in the quietest times and the most conformable strata, by changes of bottom from sand to clay or lime, or *vice versa*, produced by a change of currents, or slight changes of shore line.

Effect of Specialized and Generalized Forms.—Again, as to the nature of the process of change in the changing organism itself: Long continued prosperous times with unchanging conditions give rise to *highly specialized forms*, perfectly adapted to these conditions, but correspondingly *unadapted to other conditions*, in other words, to *rigid forms*, rigid through the accumulation of heredity for many successive generations on the same point. Generalized forms, on the contrary, are less perfectly adapted to any one set of conditions, but more easily adaptable to many kinds of conditions. They are a sort of Jack-of-all-trades and not very good at any. These are therefore more plastic to the moulding influence of a changing environment. Therefore long continued periods of quiet give rise to many specialized dominant forms, perfectly and rigidly adapted to these conditions. During the following critical period, these dominant forms are unable to adapt themselves to new conditions. Too rigid to change with the changing times, they are destroyed, while only the few and less conspicuous generalized, and therefore plastic forms save themselves by modifications in many directions adapted to the new conditions. Thus all the old forms may quickly disappear, some by extinction, and some by modification into new forms, but all the new forms come only by modification of the old.

Periodic Law Universal.—But again, and lastly: Even in most prosperous times, and in the most continuous strata, with every evidence of great fullness of life, and when, therefore, the changes of species were slow and continuous, even under these most favorable conditions, still the links between successive species are rare. In nearly all cases progressive changes seem to take place by *sub-*

stitution of one species *for* another (of course following the line of evolution), rather than a *transformation* of one species *into* another. The same thing is observed in geographical distribution of species. In fact, there is great similarity in the laws of geographical and geological distribution of species,—the distribution in space and the distribution in time. Critical periods with their unconformities in the latter, correspond to great physical barriers in the former, for in both they separate sharply distinct faunas and floras. On the other hand, conformity with its gradual changes of species in the one corresponds with gradual changes of physical conditions in latitude and corresponding changes in species when there are no barriers. In both cases the changes of species are gradual, indeed, but usually, though not always, by substitution rather than by transformation. In the case of geographical distribution we easily account for this by the dropping out of intermediate forms in the struggle for life in *all* cases, and by migrations in *many* cases. How shall we account for it in the geological distribution?

Of course, in perfectly conformable strata, in case of change of *material* of the strata, we account for it largely by local migrations through change of bottoms. But the same is often true even in a continuous unchanged stratum. Of course, again we may attribute it, as Darwin, and many since Darwin have done, to the extreme fragmentariness of the geological record. But even when the record is complete, as it sometimes is, and the number of fossil species is fairly comparable to the number of living species in similar area and time, still the same fact is observed. There must be some other cause inherent in the very nature of the process of evolution itself. On this most difficult subject I throw out the following suggestions:—

I have already said that while the *forces* and *laws* of nature are uniform in their operation, yet *phenomena*, being usually under the influence of two opposite forces, one tending to change, the other to permanency, the one progressive, the other conservative, are nearly always more or less paroxysmal. Resistance at first prevails and there is little or no change; but forces of change are meanwhile accumulating until finally resistance gives way and conspicuous changes take place rapidly. This might, if necessary, be illustrated

from every realm of nature, but it is well recognized that all phenomena are more or less periodic or paroxysmal. Now in the case here in hand, the resistance or conservative force is heredity and the force tending to change or the progressive force is the pressure of a changing environment, physical and organic. Under these conditions, progressive movement or evolution must be more or less paroxysmal. By heredity the species resist change until at last the want of harmony with the environment becomes so great that the species must either change or die. Some accept the one alternative and some the other; the generalized forms change, the specialized die. When the change begins, I imagine, it goes on rapidly until equilibrium is again restored. The change being comparatively rapid is completed in a few generations. The steps of change are therefore represented by comparatively few individuals on that account. But again the times of change would have all the peculiarities of hard times. Not, indeed, hard times for all species as are critical periods, but for some particular species. Therefore the steps of change are represented not only by a few generations but also by comparatively few individuals in each generation. For both of these reasons, therefore, there would be a comparative poverty of fossils of intermediate forms until the necessary change is completed, adaptation is restored, and life becomes abundant again.

In a word it seems to me impossible to account for the phenomena of the evolution of organic kingdom, and especially for the rarity of transitional forms, unless we recognize a law of paroxysms in evolution, the greatest ones constituting critical periods and marking the primary divisions of time, the lesser ones the subdivisions; but the law entering into even the minutest details of succession of species in the most tranquil and prosperous times.

CONCLUDING REFLECTIONS.

In conclusion, permit me to say, I have tried to give what seems to me, under the present lights, the most rational view concerning the primary and secondary divisions of geological history. I cannot for a moment hope that the view here presented is final or even nearly so. There must continue to be evolution of thought on this

as on every subject. In science, the last word is never said on any subject. Old views must give way to new, but let us not lose sight of the germs of truth contained in the old. Evolution of thought must, indeed, continue, but let us remember that evolution is by *modification*, not by destructions and recreations. Ideas are like species. In the evolution of thought some, indeed, become extinct and leave no progeny, but some are transformed into new, and all the new come only by such transformation of the old. All I can hope is that those expressed above are among the plastic ones, which will not be destroyed but changed into higher forms.

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ON

MALIGNITE,

A FAMILY OF BASIC PLUTONIC ORTHOCLASE ROCKS RICH IN ALKALIES AND LIME

INTRUSIVE IN THE COUTCHICHING SCHISTS OF POOHBAH LAKE.

BY

ANDREW C. LAWSON.

CONTENTS.

INTRODUCTION.

POOHBAH LAKE lies in the District of Rainy River, in the Province of Ontario, Canada. The detail of its geographic relations may be ascertained by an inspection of the Hunters Island sheet of the

Geological Survey of Canada.* The geographic and geologic surveys necessary for the preparation of this sheet were under the immediate direction of the writer, and were well advanced at the time of his resignation from the Canadian Survey in 1890. The work was subsequently continued and prepared for publication by the writer's assistant, the late W. H. Smith, acting under instructions from the director of the survey. Although Mr. Smith was thoroughly devoted to his work and was a very competent geographer, his duties as such had, in the earlier years of his service, precluded his giving attention seriously to geological studies, and he therefore undertook the continuation of the writer's work practically as a beginner in geological research. The vigor and ability which he displayed in the execution of that task foreshadowed a successful career had he been spared to follow up the investigations so inaugurated.

Mr. Smith being thus unexpectedly called upon to complete a work with which he was familiar, but for which he had had no especial preparation, it is not surprising, nor does it in the least reflect on his memory, that some deficiencies should exist in his account of the geology of the region and in the accompanying map. Some of these may, as opportunity presents, be filled out by the writer, with perhaps better grace than by any other investigator who may follow us in this field.

Among the more interesting points in the geology of the region which were touched upon, but not fully discussed, in Mr. Smith's report, are the rocks of Poohbah Lake; and it is the purpose of this paper to present some observations upon these rocks which, it is hoped, may have more than a local interest.

The field data are based on a somewhat hurried but geographically complete examination of the shores of the lake during two days of the last season in which the writer was engaged in exploring the region, supplemented, for purposes of mapping, by some observations by Mr. Smith on Wink Lake to the west, and two short excursions by the writer on jungle trails, one from the north shore of the lake northward, and the other from the south shore southward.

*Annual Report, Vol. V, 1890–91. Part G.

The shores of the lake are occupied for the most part by a coarse syenite-like rock which is intrusive in the mica schists of the Coutchiching series of the Ontarian system of the Archæan. This intrusive mass has a roughly elliptical shape in ground plan, with a longer diameter of not less than six miles, and a shorter diameter of about three miles. It has the same intrusive relation to the Coutchiching schists as do the normal Laurentian biotite granites and hornblende granites and their gneissic modifications. The mica schists strike around the mass so as to inclose it on all sides

FIGURE 1.—Sketch map of Poohbah Lake; showing relation of the laccolite mass to the Coutchiching schists. A, nepheline-pyroxene-malignite; B, panidiomorphic-gneissic-facies of the same; C, garnet-pyroxene-malignite; D, a minor facies of the same; E, amphibole-malignite; F, Coutchiching schists. The numbers 495, 501, 503, 506, and 510 indicate where specimens were taken. Scale, two miles=one inch.

The schists are well exposed on the north side of the lake and at its southwest extremity; and the known distribution of the same rocks in the region to the north, west, and south of the lake is ample warrant for the approximate delimitation of the intrusive mass indicated on the accompanying diagram, Fig. 1. To the northwest of the

lake only is there any doubt as to the position of the line of demarkation between the intrusive and intruded rocks. Along the north shore of the lake and on the shores of the narrow arm which leads to the outlet, the dip of the mica schists is to the N. N. W. away from the intrusive mass at angles of about 60°, but locally inclined as high as 80°. At the northeast corner of the lake, on the same line of strike, the schists are vertical or dip somewhat toward the mass. At the southwest end of the lake the schists are highly garnetiferous and dip beneath the mass toward the northeast at about 60°.

As will appear in the following pages, the intrusive mass is petrographically distinct from the ordinary Laurentian intrusives of the region, and this fact, together with its limited extent, its isolation in the midst of a schist belt, and the inward dip of the schists at the southwest end of the lake, suggest with much probability that it is laccolitic in its structural relations to the Coutchiching rocks, the latter being without doubt metamorphic sediments. In age the mass belongs to the Archæan in the same sense and for the same reasons as do the granites and gneisses of the region which are commonly referred to as Laurentian, and which have a batholitic relation to the Ontarian rocks.

This laccolitic mass, although very clearly a geological unit, is not petrographically uniform. Three distinct types of rock may be readily discriminated in the field, and each of these presents subordinate variations. All three types have strongly-defined chemical and mineralogical characters, which preclude their specific identification with any other rocks known to the writer. In their structure, also, they present several features of exceptional interest. While these rocks thus appear on chemical and mineralogical grounds to be new types, they have a certain community of character which warrants their being grouped in a single family. To designate this family, it is proposed to use the term *Malignite*, from the Maligne River, the chief stream of the immediate district in which these rocks occur.

The Malignites are characterized as basic, holocrystalline, plutonic rocks, rich in alkalies and lime. Iron is present in but moderate proportion for rocks of such basicity, and is practically wholly

combined in the silicates, there being but mere traces of iron ores. Both iron and magnesia are, on the other hand, more abundant than is usual in the alkali-rich plutonic rocks. Mineralogically, their constant characteristic is the prominence of orthoclase, with which is often associated acid plagioclase in microscopic intergrowth. Quartz is wholly absent. The constant ferro-magnesian silicate is ægerine-augite, which may predominate, with but a moderate admixture of biotite, or may be subordinate and intergrown with a preponderant soda-amphibole, biotite being present as before. In one of the three types of malignite, melanite is an essential and very prominent constituent. In another, nepheline enters into the composition of the rock.

Such alkali-lime-rich rocks with low silica and moderate alumina, iron, and magnesia, find no place in the existing families of plutonic rocks. They are clearly not granites. They are too low in silica and too high in lime, and rather high in alkalies for syenites, if that term is to have any precision of significance. They have certain affinities with the nepheline-syenites; but here again their characteristically high lime contents, and in a less degree their low silica, bars the way to their admission to the family. Besides, only one of the three types contains nepheline, and that is petrographically, as well as geologically, much more closely affiliated with the other two which have no nepheline than it is with the nepheline-syenites. Neither are they to be placed in Brögger's newly-established family of the monzonites, since they are explicitly excluded by that author's definition of the characteristics of the family,* although the latter is a generously hospitable one for many a stray rock of hitherto dubious pedigree. Being orthoclase rocks, they belong neither to the theralites nor the diorites nor the gabbros. How then shall we class them? Squeeze them in somewhere in an existing family, no matter how it vitiate the characteristics of the family? Such has been a too prevalent custom, and the process has gone on till some of our rock families have become unduly distended with foreign elements, each succeeding one more remote from the type than its predecessor, and relief is effected only by a violent disgorgement. By such a process of disgorgement

* Die Eruptionsfolge bei Predazzo, pp. 53, 54.

has the new plutonic family of the monzonites come into existence under the masterly treatment of Brögger, and a great distress is lifted from the diorites and syenites. It seems wiser to avoid the confusion arising from such periodic evictions from the older families by freeing ourselves from the crude idea that the number of rock families must be limited to those we already recognize. A cramped scheme of classification in the early stages of the development of a science such as petrography is certainly a serious hindrance to the progress of philosophic ideas. It is better to err rather on the side of a somewhat diffuse classification at first, and to condense as relationships become clearer and more settled. With these considerations in mind the writer ventures to face a well-known and often-expressed prejudice against the introduction of new rock names, and to propose the establishment of the new family of the *Malignites* to accommodate the new rock types described in the following pages. These may be referred to as *amphibole-malignite*, *garnet-pyroxene-malignite*, and *nepheline-pyroxene-malignite.* In the petrographical descriptions the last named will be considered first.

NEPHELINE-PYROXENE-MALIGNITE.

Macroscopic Characters.—The rock is of a light gray color, being composed of light and dark colored constituents in about equal proportions, and presents the general aspect of a rather feldspathic dolerite of medium texture. The light-colored constituents comprise: (1) Orthoclase in part fresh and glassy and in part milk white; (2) a dead white mineral, nepheline, in a more or less decomposed condition; and (3) glassy, bright greenish-yellow apatite. The dark constituents are: (1) Lustrous black, elongated prisms of pyroxene in great abundance; (2) occasional foliæ of brownish black biotite; and (3) somewhat rare grains of titanite. When critically examined the hand specimens show by the uniform reflection of the cleavages that the orthoclase is present in large individuals, as much as 4 cm. in diameter, but the space occupied by the feldspar is so charged with all the other constituents of the rock that it does not otherwise appear prominent; and if it were not for the cleavage reflections, there would be no suggestion of its occurring in large individuals. In hand specimens it appears rather

as an aggregate of small grains in between the augites. The nepheline may be discriminated from the feldspar as dull white spots, which are quite abundant, but which present no sharply recognizable boundaries to the unaided eye. The apatite is remarkably abundant and occurs in elongated grains ranging up to 3 mm. in greatest diameter, which by reason of their yellow color, vitreous lustre and rather high refractive power, are prominent features of the hand specimens. The pyroxene prisms are several times longer than their breadth. The planes in the prismatic zone are well developed, but no terminal planes could with certainty be detected. The prisms have all possible orientations. The biotite occurs in plates which occasionally attain a diameter of 5 mm. It is, however, usually much smaller, and is a subordinate constituent of the rock.

The general gray color of the rock is occasionally blotched with darker patches, in which the pyroxene, in very much smaller individuals, preponderates greatly over the light-colored constituents.

Structure.—Under the microscope a remarkable feature of the rock is the poikilitic relation of the orthoclase to all the other constituents. Over large areas it extinguishes uniformly between crossed nicols, thus proving its physical continuity, although in the plane of the section it frequently appears in discrete areas. In several sections about 2x1.5 cm. in extent only one individual of orthoclase is present, and in this are imbedded all the other constituents. It is evident from this relationship that the orthoclase was the last mineral to crystallize, and that it represents, in fact, the residual magma after the other constituents had separated. None of the other minerals thus inclosed in the orthoclase appears to have any definite relation in space with reference to the host, but have a perfectly haphazard orientation. The large crystals of orthoclase, which thus serve as the paste of the rock, have no geometrical boundaries but are allotriomorphic with reference to one another. The fundamental structure of the rock may, therefore, be said to be allotriomorphic granular, and all of the constituents other than the orthoclase are of the nature of idiomorphic phenocrysts. None of the minerals of the rock seems to have separated in more than one generation if we leave out of considera-

tion the occasional patches of fine-grained black rock, which probably represent local more basic secretions.

The idiomorphic constituents only occasionally exhibit the rectilinear outlines of the ideally perfect crystals. Their constant approximation to these outlines is, however, characteristic of them.

Mineralogical Details.—The orthoclase is characterized throughout the rock by a molecular tension which manifests itself in undulatory extinctions. This is very probably a direct consequence of the conditions under which it crystallized. The orthoclase being the last product of the crystallization of the magma and forming large individuals inclosing all the other constituents, it would naturally result that there would not be opportunity for the adjustments due to change of density at the point of crystallization, or during cooling after crystallization. The orthoclase also presents under low powers a very dusty appearance, due to the abundance of minute interpositions. These are of two kinds: (1) Slender opaque rods frequently arranged in parallel position resembling schillerization products, and (2) minute opaque rounded bodies scattered irregularly throughout the mineral. There are, also, rarely occurring transparent microlites inclosed in the orthoclase, but no liquid inclusions were observed. No twinning structure was observed in any of the slides. For the most part the orthoclase is fresh, but it is cloudy in places as a result of decomposition. Both cleavages, parallel to OP (001) and to $\infty P\breve{\infty}$ (010) are distinctly observable. In cleavage flakes parallel to OP, it was determined by aid of the quartz wedge that $\mathfrak{a}$ lies parallel to the trace of the clinopinacoidal cleavage and that $\mathfrak{c}$ lies normal to the same direction. The refractive power and double refraction are those of orthoclase.

The chemical character of the orthoclase was tested by subjecting small grains of it to the action of hydrofluosilicic acid, the result being an abundant crop of cubes of fluosilicate of potassium, with an exceedingly few more minute hexagonal crystals of fluosilicate of sodium, and occasional prismatic crystals, with rhombohedral terminations, which represent probably the corresponding compound of iron derived from the interpositions in the feldspar. The result of the test shows that sodium is present in the feldspar

in the merest traces, and that we have to deal with a true potash orthoclase. The powder of the orthoclase after digestion with hot hydrochloric acid remained unacted upon. Its specific gravity is between 2.56 and 2.57.

The pyroxene, which is abundant, is a deep green pleochroic variety, with a pronounced elongation in the direction of the *c* axis. It has the usual high refractive index, strong double refraction and distinct prismatic cleavage of the augites. In clinopinacoidal sections the maximum observed value for the extinction angle $\mathfrak{c} : c$ is 59°. The pleochroism is in shades of green and yellow, but can not be adequately expressed by the simple formula usually employed. In sections normal to the acute bisectrix the optically positive character of the mineral is easily established by the use of the quartz wedge. Such sections contain $\mathfrak{a}$ and $\mathfrak{b}$, and the orientation of these axes is readily determined by the interference figure. These sections show a feeble pleochroism $\mathfrak{a}$=sap green, $\mathfrak{b}$=whitish or yellowish green. The absorption is $\mathfrak{a}>\mathfrak{b}$, but in many cases the difference of absorption is so slight that no distinction can be made, and $\mathfrak{a}=\mathfrak{b}$. In sections parallel to $\infty P\grave{\infty}$, containing the axes $\mathfrak{a}$ and $\mathfrak{c}$, the pleochroism is also comparatively feeble, though generally more pronounced than in the last case; $\mathfrak{a}$ = sap green, $\mathfrak{c}$ = yellowish green to yellowish. The absorption is $\mathfrak{a}>\mathfrak{c}$. In sections normal to the obtuse bisectrix, containing $\mathfrak{b}$ and $\mathfrak{c}$, the pleochroism is much stronger. In these sections $\mathfrak{c}$ = yellow to amber, $\mathfrak{b}$ = whitish green. The absorption is $\mathfrak{b}>\mathfrak{c}$. From these observations the general formula would be $\mathfrak{a}\geqq\mathfrak{b}>\mathfrak{c}$, and the sections parallel to $\infty P\grave{\infty}$ containing $\mathfrak{a}$ and $\mathfrak{c}$ might from this formula be expected to exhibit a pleochroism not less pronounced than any other section. This, however, is not the case. The very pronounced yellow and green pleochroism in sections approximately transverse to *c*, and showing the emergence of an optic axis, is a persistent feature of the mineral. If the axes of absorption are dispersed in the plane of symmetry, as has been suggested by Laspeyres*, the yellow $\mathfrak{c}$ ray might be nearly normal to the optic axis, which lies near to *c*. But inasmuch as the clear yellow to amber does not appear in clinopinacoidal sections, this supposition of the dispersion of the axes of

*Z. f. Kryst, IV. 1880, 454.

absorption does not satisfactorily explain why the pleochroism should be so much more pronounced in sections transverse to c than in all other sections. The dispersion is $\rho < v$.

In thin sections the planes of the prismatic zone are fairly, sharply defined. Terminal planes, however, are absent, or are represented occasionally by blunted outlines. In size the prisms range from very small dimensions to a length of about 5 mm. and a breadth of from .5 to 1 mm. The average size of the prisms is probably about 2.5 x .5 mm. There is no pronounced extension of the crystals in the plane of the orthopinacoid. Twinning is not uncommon according to the usual law in which $\infty P\bar{\infty}$ is the twinning plane. Minute interpositions and secondary products arising from alteration of the pyroxene are entirely lacking, but there are occasional inclusions of the other constituents of the rock, such as apatite, and sometimes, also, grains of magnetite, the latter mineral not being otherwise represented in the rock. Chemically the presence of sodium in addition to the magnesium, calcium, and iron was proved by treating minute grains of the pyroxene, with hydrofluosilicic acid. An abundant deposit of the characteristic hexagonal crystals of fluosilicate of sodium was obtained. From the above-noted characters it is evident that the pyroxene is an *ægerine-augite*.

The nepheline occurs in the rock under different conditions of crystallization. For the most part it is scattered through the orthoclase in idiomorphic, cloudy white crystals which rarely exceed 1 mm. in diameter, the average size being about .5 mm. These crystals show well-defined crystal boundaries in the cross sections, which are commonally hexagonal, pentagonal, rectangular, etc., in shape. They have evidently preceded the orthoclase in the crystallization of the magma. Other occurrences are allotriomorphic with reference to the prisms of ægerine-augite. These, too, have evidently antedated the orthoclase. There are, however, in the slides, areas of nepheline which have blurred and hazy or irregular outlines interlocking with the orthoclase, in which they are imbedded as if the mineral had in these cases crystallized simultaneously with the orthoclase. Finally, there are occasional areas where the nepheline and orthoclase present a most remarkable micropegmatitic in-

tergrowth, as will be described more particularly below. In general, it seems to be true that the nepheline crystallized after the ægerine-augite, and for the most part before the orthoclase, but that a subordinate portion of it crystallized simultaneously with the latter.

The nepheline is generally charged with decomposition products, but remains sufficiently intact to reveal its optical character. Numerous sections were observed cut approximately normal to *c*, which yielded in convergent light the uniaxial interference figure. By the aid of the $\frac{1}{4}\lambda$ mica plate, the mineral was proven to be negative. The index of the refraction is low, and the double refraction is weak. Cleavages are occasionally detected, and to these the extinction is parallel. Slender colorless microlites (apatite) are sparingly present as inclusions. The decomposition products are either fibrous and polarize in brilliant colors with parallel extinction, or they are cloudy kaolin-like aggregates. The development of these secondary products seems to have induced a molecular tension in the undecomposed nepheline, since between crossed nicols it generally manifests an undulatory extinction.

When treated with dilute hydrochloric acid, the surface of the thin sections of the nepheline gelatinizes and stains readily. If, prior to staining, the solution be allowed to evaporate, an abundant deposit of cubes of sodium chloride is obtained. These microchemical reactions were repeated several times on different slides with uniform results, and, in some instances, grains were so treated which had previously yielded the uniaxial interference figure. The character of the mineral as nepheline is thus established beyond question.

An interesting feature of the rock is the micropegmatitic intergrowth of the nepheline and orthoclase. This is observable in a limited number of areas which appear as somewhat cloudy spots in the midst of the fresh pellucid orthoclase. Under high powers of the microscope, they present a curious vermicular appearance, resembling, if the homely simile may be used, a layer of vermicelli in a plate of clear soup. The vermicular rods are usually very slender and long. They are disposed either in a parallel or slightly divergent arrangement, or present a curiously contorted appearance. Sometimes they have a comb-like appearance, and are arranged as a series of club-like bodies nearly normal to an axis composed of a

bundle of slightly divergent rods into which the lateral club-like bodies pass. These vermicular rods sometimes overlap and cross one another, but never intersect. Different rods may be seen one above the other in the thickness of the slide. They frequently branch from a common stem. These rods are composed of cloudy nepheline, and in the ordinary preparations the structure is difficult to study. If, however, the slide be treated with dilute hydrochloric acid and stained with fuchsine, the nepheline rods are very sharply marked off from the orthoclase with which they are intergrown, the rods being colored, and the orthoclase colorless. The orthoclase extinguishes sharply as a unit in common with that beyond the area of intergrowth. Figure 2 illustrates the morphology of the intergrowth, which seems to be very similar to an intergrowth of the same minerals in the rock borolanite described by Teall.*

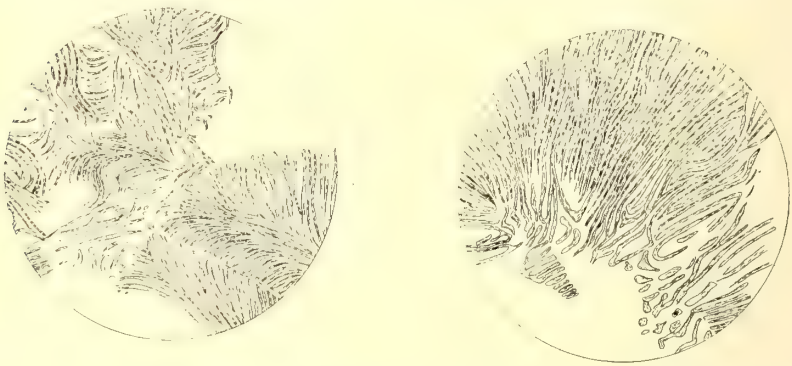

FIGURE 2.—Intergrowths of orthoclase and nepheline in nepheline-pyroxene-malignite. The shaded parts are nepheline and the clear orthoclase.

The apatite is remarkable for its abundance, and for the size of its crystals. It occurs in stout prisms having a maximum length of about 3 mm. These are very striking features of the slides, and the mineral can not be regarded as playing a merely accessory role. The crystals are all perfectly fresh and water clear, but exhibit quite a marked relief, and a very notable total reflection of the light on the borders and along the cracks, the presence of the latter being a

*Trans. Royal Soc., Edin. Vol. XXXVII, Pt. I, No. 11, 1892.

constant feature. The mineral has the usual weak double refraction of apatite, polarizing in blue grays of the first order. It is uniaxial and optically negative. The crystals differ from the apatite microlites usually observed as accessories in many rocks in the somewhat uneven or obtusely serrate outline of the crystal boundaries. The terminations of the prisms are often rounded. Fragments of the mineral are easily isolated in a pure condition. These fragments dissolve in hydrochloric acid, and when to the solution a minute drop of sulphuric acid is added, a copious precipitate of characteristic gypsum crystals is obtained. When fragments are dissolved in nitric acid and treated with ammonium molybdate, the canary yellow precipitate indicative of phosphoric acid is obtained. The specific gravity of the mineral as determined by the use of Klein's solution is 3.250. The identification of the mineral as apatite is thus placed beyond a doubt.

The biotite calls for no special description, as it is very sparingly represented in the rock, and exhibits the ordinary well-known characters. As is usual with the mineral, its boundaries are irregular, and have a corroded appearance. The titanite is quite accessory to the general mineralogical composition of the rock, but occurs in grains sufficiently large to permit of its positive identification. In one slide a few grains of pyrite were detected, but the occurrence of this mineral is quite exceptional.

Chemical Characters.—An analysis of the rock was made for the writer, by Mr. F. L. Ransome, Fellow in the Department of Geology of the University of California, to whom the writer here desires to express his obligations. The results of this analysis are given in column I. Columns II, III, IV, V, and VI are analyses of Vesuvian leucitophyres taken from Roth's tables,* while column VII is an analysis of borolanite, taken from Teall's description of that rock.†

*Beitrage zur Petrographie, etc. K. Akad. d. Wiss. Berlin.
† *Loc. cit.*

	I.	II.	III.	IV.	V.	VI.	VII.
SiO_2	47.85*	48.83	49.15	48.59	48.54	47.63	47.8
Al_2O_3	13.24†	15.34	13.37	19.58	14.86	15.11	20.1
Fe_2O_3	2.74	7.39	6.65	4.38	4.17	6.07	6.7
FeO	2.65	3.34	5.88	4.56	4.82	3.34	.8
CaO	14.36‡	13.63	10.73	9.12	11.89	15.70	5.4
MgO	5.68	4.65	5.30	3.12	5.75	4.66	1.1
Na_2O	3.72	1.41	3.08	2.15	2.71	1.18	5.5
K_2O	5.25	3.68	6.55	6.27	6.45	3.87	7.1
H_2O	2.74	....	....	.12	.16	1.61	2.4 (ig.
P_2O_5	2.42	1.83	....	2.04	....	1.65	....
SO_3	....	.02	....	.15	....	.05	.4
Cl	....	trace	....	trace	....	.06	(Baryta .8)
TiO_2	....	....	....	....	.21	....	.7
MnO	....	....	....	....	1.18	....	.5
Total	100.65	100.12	100.71	100.08	100.92	100.93	99.3
Sp. g.	2.879	2.76			2.65	2.74	

* Mean of 47.91 and 47.79.
† Mean of 13.33 and 13.16.
‡ Mean of 14.54 and 14.19.

With very moderate digestion 28.14 per cent. of the rock dissolves in hydrochloric acid.

An attempt was made to estimate the proportions in which the constituent minerals are present in the rock, and the following results were obtained:—

		Proportion of Minerals.	Specific Gravity.	Product.
Ægerine-augite..	Ægerine........ 5.60 Diopside........ 27.92 Hiddenbergite 9.50 Augite........... 5.15	48.17	3.299 *d*	158.91
Orthoclase		20.90	2.56 *d*	53.51
Nepheline		19.62	2.60 *a*	51.01
Apatite		5.81	3.25 *d*	18.88
Biotite		2.00	2.90 *a*	5.74
Titanite		1.00	3.50 *a*	3.50
Water		2 70	1.00	2.70
		100 20	*d*=determined *a*=assumed	294.35

The specific gravity of the rock as thus estimated should be 2.93, while the actual specific gravity is 2.879. We have thus a check upon the approximate estimate of the proportion of the different minerals present.

Petrographic Relations.—If the rock having the mineralogical characters set forth in the preceding pages were the only facies of the Poohbah Lake laccolite, and the rock were considered only as a mineralogical aggregate, without reference to its chemical composition, it would probably be classed with the nepheline-syenites. Its intimate mineralogical affiliation with other important facies of the same mass, which can not possibly be classed with the nepheline syenites on mineralogical grounds, serves, however, to cast serious doubt upon such a reference. This doubt leads rapidly to a denial of the correctness of the reference the moment we inspect the chemical analysis of the rock and compare it with that of representative nepheline-syenites. We see at once that its low silica contents, 47.85 per cent., and the high lime, 14.36 per cent., are alone sufficient to segregate the rock from the nepheline-syenites, heterogeneous as that family is. The proportion of magnesia, 5.68 per cent., is, moreover, quite at variance with that of the nepheline-syenites. It is worthy of note, too, that the potash is in excess of the soda, while the reverse is generally true of the nepheline-syenites. On the other hand, the nepheline-pyroxene-malignite is chemically closely akin to certain Vesuvian leucitophyres, as may be seen by an inspection of the analyses given in the table. From these it chiefly differs in its more moderate content of iron and alumina. It appears therefore that we have in this malignite the plutonic equivalent of a well-known volcanic rock—the leucitophyre of Vesuvius.

In addition to the broad characteristics which segregate this rock from the nepheline-syenites, certain other features may be alluded to, which, although from a taxonomic point of view are probably of minor or varietal significance, have considerable intrinsic interest. These are the peculiar poikilitic structure of the rock, the total absence of plagioclase, and the remarkably high proportion of phosphoric acid revealed by the analysis. None of these is to be held a distinctive or constant feature of this chemical type of basic plutonic rock; but they combine to add interest to this occurrence of it, and to emphasize its unique character. It is, moreover, noteworthy that in its high contents of phosphoric acid the nepheline-pyroxene-malignite is even approximately paralleled by no other rocks save the Vesuvian leucitophyre, with which it is on other grounds correlated.

Panidiomorphic Gneissic Facies.—There are many variations in the general appearance of the nepheline-pyroxene-malignite in its exposures on Poohbah Lake. These are chiefly due to variations in the coarseness of the rock, or to the degree of disintegration of the rock. There is, however, besides these a distinct local facies which deserves special notice, although, unfortunately, its relations to the main mass were not determined beyond the fact that the one graded with the other. It is a peculiarly foliated or platy rock, which, although having the same mineralogical composition as the normal facies, presents a very different structure. The constituent minerals are, as before, orthoclase, ægerine-augite, nepheline, apatite, titanite, and biotite. The relative abundance of these is, however, somewhat changed. The orthoclase is relatively more abundant and the ægerine-augite less so than in the non-foliated facies. Nepheline occurs in about the same proportions, but the apatite is more sparingly represented. Titanite is more plentiful than biotite, but both play an accessory rôle.

The structural differences between this facies and the normal type of nepheline-pyroxene-malignite are radical. The orthoclase instead of crystallizing in large allotriomorphic masses having a poikilitic relation to all the other constituents is here idiomorphic. It occurs in plates tabular to $\infty P \breve{\infty} (010)$ ranging in size from 3 to 7 mm. and from .5 to 1 mm. thick. The ægerine-augite commonly shows idiomorphic forms or approximations to these, and appears in general to have in part antedated the orthoclase and in part been contemporaneous with it in crystallization. The nepheline is idiomorphic usually, and inclosed in the orthoclase, but occasionally is moulded against the earlier ægerine-augites. The apatite is idiomorphic, but the titanite is allotriomorphicly interlocked with the ægerine-augite and rarely shows its characteristic crystal outlines. In structure, therefore, the rock may be said to be panidiomorphic. This statement, however, fails to express the most striking structural feature of the rock. This consists in the parallelism of the orthoclase plates. Since these plates are the chief constituent of the rock, their disposition in one plane, with but a moderate amount of overlapping, as with shingles on a roof, gives the mass a very platy or scaly appearance, when viewed in fractures parallel to this

GARNET-PYROXENE-MALIGNITE.
Natural Scale.

plane. It presents a distinct gneissic foliation in fractures transverse to the plane in which the plates lie. The foliation is clearly original, and there is no suggestion of cataclastic or even protoclastic structure in thin sections of the rock. The orthoclase is remarkably free from the molecular tension which is so characteristic of the normal facies of the rock. The plates of orthoclase are commonly slightly curved, and in some cases even distinctly bent, but the phenomena of extinction due to this fact are quite different from the optical tension shown by the poikilitic orthoclase of the normal rock.

The minerals of this facies of the rock have generally the same characteristics as in the normal type. The ægerine-augite presents the same pleochroism. The orthoclase is charged in the same manner with dusty and rod-like interpositions, the latter usually arranged in definite planes and presenting all the characteristics of "Schillerization" products. The orthoclase differs, however, from that of the normal type in being frequently twinned on the Carlsbad law. It is practically quite fresh and sanidine-like, kaolinization products being only occasionally observed in small areas. The nepheline shows the same degree of alteration to cloudy products, and the large apatites have the same irregular cracks and irregularity in detail of their crystal boundaries as in the normal rock.

THE GARNET-PYROXENE-MALIGNITE.

General Features.—This malignite presents at least two fairly distinct facies, which grade into one another in the same mass. The dominant of these occupies the greater part of the south side of the lake, being interrupted only by limited areas of rocks of the nepheline-pyroxene-malignite type, whose special relations to the garnet-pyroxene-malignite are not well defined, owing to the dense vegetation. The minor facies is confined, so far as observation goes, to the northwest corner of the west end of the lake near the contact with the mica schists. The dominant facies presents a remarkable appearance and appeals to the petrographer's eye as a unique rock. The most prominent mineral is orthoclase, which appears in the form of huge, thick plates of a light flesh tint imbedded in parallel position in a dark green, moderately fine-grained

holocrystalline matrix. These idiomorphic orthoclases are tabular, parallel to the clinopinacoid, and commonly attain a length of from 4 to 6 cm., and a thickness of from 3 to 5 mm. They are in many cases twinned on the Carlsbad law. The basal cleavages are in all cases well developed. In addition to these large crystals there are also smaller irregular grains of the same feldspar scattered through the dark green matrix of the rock, but still showing a more or less pronounced tendency to assume tabular forms and thus grade into the large porphyritic crystals. It is evident from an inspection of the rock that the porphyritic orthoclases antedate the matrix in which they are imbedded, but that the crystallization of the latter set in before the orthoclase molecule was completely precipitated from the magma, so that the residual orthoclase crystallized with and became involved in the aggregate of minerals which constitute the matrix. There is thus no hard and fast line between the bulk of the orthoclase which appears as large crystals and the moiety having the smaller and less regular forms. See Plate 18.

Microscopic Characters.—Under the microscope the orthoclase shows a constant and well-developed microperthitic intergrowth with albite. The latter mineral is readily distinguished from the orthoclase by its somewhat stronger double refraction, its difference of extinction, and in many cases by its lamellar twinning. It is identified by its extinction angle against the basal cleavage in cleavage flakes parallel to the clinopinacoid of the orthoclase. In these flakes the orthoclase has an extinction angle of about 4°, and the plagioclase an angle of 16° to 18°, with an average of 17° 22′, so that there can be little doubt of its being nearly pure albite.

The albite is intergrown with the orthoclase in thin lenticular plates, which lie parallel to the orthopinacoid of the latter and give striped sections in the zone P : M as of overlapping spindle-shaped bodies. In these striped sections the orthoclase is generally somewhat cloudy, while the albite is clear, so that the striped appearance is apparent without the use of crossed nicols. In sections parallel to the orthopinacoid the orthoclase gives an interference figure in which the plane of the optic axes lies parallel to the trace of the basal cleavage. Sometimes the albite of the microperthite appears to be in optical continuity with grains of albite on the periphery of

the orthoclase, and there are occasional quite separate grains of the albite in the slides, which are doubtless genetically connected with that of the microperthite. These are the only plagioclase feldspars in the slides.

The dark green matrix in which these large idiomorphic orthoclases (microperthite) are imbedded is a hypidiomorphic granular aggregate of ægerine-augite, melanite, biotite, titanite, and apatite, stated in the order of their abundance, together with the subordinate proportion of microperthite and albite above alluded to. As accessory minerals occur magnetite and hematite in exceedingly sparing quantities in a few slides. Of these minerals the titanite and apatite are commonly idiomorphic, although occasionally they are quite irregular in outline and are allotriomorphicly interlocked with the other minerals. The three principal constituents, ægerine-augite, melanite, and biotite, seem to have crystallized simultaneously and are entirely allotriomorphic, although the pyroxene shows the usual tendency to elongation parallel to *c*.

The ægerine-augite has the same optical characters as those already described for its occurrence in the nepheline-pyroxene-malignite. In some few cases, however, it is of a less deep green color and may indeed be nearly colorless. These are rather exceptional occurrences, and are doubtless due to a local poverty of the ægerine molecule. Twinning on $\infty P \bar{\infty}$ is common. The melanite is in the form of reddish brown to yellowish grains, which are strictly isotropic. They are quite fresh and contain no inclusions as a rule. They have the high refractive index of the garnets and their characteristic irregular cracks. A coarse powder of the rock on being treated with hydrofluoric acid for 24 hours dissolved all the other minerals and left the melanite intact.

The biotite is a brown variety, shading into green locally, and calls for no especial comment.

The titanite appears in thin section in the form of brownish yellow crystals, which commonly exhibit the characteristic rhombic sections of that mineral. These crystals are usually prominent features of the slides and attain a size of 3 mm., though commonly they are about 1 mm. in length. They are more abundant than the proportion of titanic acid found in the analysis would lead one to

suppose. The pleochroism is quite pronounced in shades of brownish red and yellow. In sections normal to the acute bisectrix the mineral proves to be optically positive.

The apatite has the same characters as those given for the mineral in the nepheline-pyroxene-malignite. The crystals are, however, smaller and less abundant than in that type of rock. The hematite is represented only by an occasional scale in some of the slides. It is of a deep red color, translucent on the margins, but opaque in the thicker central portions. A few grains of magnetite may be found by careful search, usually inclosed in the ægerine-augite. A canary yellow pleochroic mineral is found in some of the slides, but, on account of small dimension of the grains, could not be satisfactorily determined. It has a strong double refraction, but lower refractive index than epidote, and the extinction angle measured against the direction of elongation has a high value.

Chemical Analysis.—For the following analysis of this interesting rock, the writer is indebted to Mr. W. C. Blasdale, instructor in chemistry in the University of California.

Analysis of Garnet-Pyroxene-Malignite.

SiO_2	51.88
Al_2O_3	14.13
Fe_2O_3	6.45
FeO	.94
CaO	10.81
MgO	3.44
Na_2O	6.72
K_2O	4.57
TiO_2	.33
P_2O_5	.96
H_2O	.18
Total	100.41
Sp. g.	2.88

From the above data it will be apparent that this malignite approaches in its mineralogical and chemical characters the basic

augite-syenite, laurvikite, of Brogger.* It differs rather radically, however, from that type of rock in being more basic, and in having a lower proportion of alumina, and higher proportions of lime and ferric oxide. These chemical differences find their mineralogical expression in the abundance of melanite. The somewhat higher proportion of magnesia is to be correlated with a larger proportion of pyroxene than is found in laurvikite. The structure of the rock, finally, is quite different from that of laurvikite.

Minor Facies.—The minor facies of the garnet-pyroxene-malignite, which occurs at the northwest corner of the southwest end of the lake, differs in appearance from the prevailing type, from the fact that the feldspar is more abundant, and is very much smaller in size, so that the rock presents a more uniformly gray color, and no striking contrast between the porphyritic constituents and the matrix. The feldspars, however, have the same platy habit, and exhibit a feeble tendency to parallelism. Those which are porphyritic have rather poorly defined boundaries, and they grade insensibly into the feldspar of the matrix. The structure of the rock as a whole may be fairly described as hypidiomorphic granular, although the tendency to platy habit extends to all the feldspar of the rock. Interlocked with the feldspar in allotriomorphic relation are melanite, ægerine-augite and biotite. Titanite and apatite are prominent, as before, but are sometimes also allotriomorphic. The melanite never shows crystal boundaries. Mineralogically the facies presents a distinction from the prevailing type in the greater proportions of melanite and biotite which are present, and the less proportion of ægerine-augite. Its chemical character has not been fully determined, but a partial examination of the rock kindly made for the writer by Miss S. Sharpe, in the chemical laboratory of the University of California, shows that it is somewhat more basic than the prevailing facies. This examination showed the presence of SiO_2 48.86, Al_2O_3 17.40, Fe_2O_3 7.67, FeO .48, Na_2O 8.13, K_2O 2.81. The specific gravity of the rock is 2.93.

AMPHIBOLE—MALIGNITE.

Mineralogical Composition.—That portion of the mass which is

*Die Mineralien der Syenit-pegmatitgänge, etc. Z. f. K. u. M. 16, 1890.

exposed along the northern shores of the lake, and which is here termed amphibole-malignite, may be best described by comparing it with the garnet-pyroxene-malignite. In its general aspect as viewed in the hand specimens, the rock differs from the garnet-pyroxene-malignite in the fact that the orthoclase crystals are smaller, and less sharply defined, while the dark green to black matrix in which they are imbedded is much coarser, owing to the predominance of a lustrous black amphibole in grains of large size. The feldspars have the same habit as before, except that their edges are ragged in detail, and that a considerable proportion of the groundmass is involved with or inclosed in the crystals, particularly on their periphery. There is also a less pronounced parallelism in the disposition of the orthoclase, although the rock is still distinctly gneissic. When viewed in thin sections, other mineralogical differences become apparent. As a result of the preponderance of the amphibole, the ægerine-augite is quite subordinate in amount, and is intergrown with the amphibole. The melanite, which is so characteristic a feature of the slides of the garnet-pyroxene-malignite, is wholly wanting. Biotite plays about the same rôle. Titanite is less abundant, and apatite remains about the same. The black amphibole proves to be difficult of investigation in thin sections, owing to its remarkably strong absorptive powers. As near as could be ascertained, it has moderately low extinctions on *c*, viz.: 12° to 21°, although it can not be said with confidence that 21° is the maximum angle. The disposition of the axes of elasticity could not be established, but if we assume them to be as in arfvedsonite, the pleochroism is $\mathfrak{a}$=deep green blue, $\mathfrak{b}$=deep greenish brown, $\mathfrak{c}$=dull yellowish green. Absorption, $\mathfrak{a}>\mathfrak{b}>\mathfrak{c}$. The hornblende cleavages are strongly developed, and the characteristic value for the prismatic angle was obtained by measuring cleavage fragments on the goniometer. Leaving aside the large orthoclases (microperthite), the structure of the rock is like that of the garnet-pyroxene-malignite hypidiomorphic granular, the titanite and apatite being the only idiomorphic constituents in the coarse groundmass in which the porphyritic orthoclases are imbedded.

Chemical Analysis.—The following analysis of the rock was very kindly made for the writer by Mr. J. W. Sharwood, instructor in chemistry in the University of California.

Analysis of Amphibole-Malignite.

SiO_2	51.38
Al_2O_3	15.88
Fe_2O_3	1.48
FeO	4.37
CaO	8.62
MgO	4.43
Na_2O	7.57
K_2O	4.20
P_2O_5	.98
TiO_2	.12
H_2O	.42
Total	99.45

As compared with the garnet-pyroxene-malignite, the chief features of interest in this analysis are that, while the silica and total alkalies remain about the same in the two rocks, there is a decrease in lime and ferric oxide in harmony with the absence of melanite and an increase in ferrous oxide and soda in harmony with the replacement of ægerine-augite by arfvedsonite.

CONCLUDING REMARKS.

The interest attaching to the rocks described in the preceding pages is twofold. To the systematist they furnish new material for any detailed scheme of classification of rocks. To the student of petrogenesis, to whom artificial schemes of classification are liable to be a hindrance rather than a help, they afford another instance of a very sharply-defined petrographic province in which the different types of rock are undoubtedly the products of differentiation from a common magma. As a problem in magma differentiation the field evidence and the material collected are unfortunately both two scant to permit of a satisfactory discussion. A few closing observations upon the inter-relations of the three types of malignite may, however, be offered. From the sketch map, Fig. 1, it will be apparent that the most basic or nepheline bearing type is quite subordinate in extent to the other two types

of rock, and that neither direct observations in the field nor inferences from the general distribution of the rocks suggest that it occupies a peripheral relation to the mass of the laccolite. In current discussions on magma differentiation it is usually assumed that the more basic portions of the products of crystallization in a magma basin are to be found on the periphery of the mass. This is undoubtedly true in many well-known cases. That it should be laid down as a general law is, however, questionable. The familiar phenomena of basic secretions in various rocks seem to have no genetic connection with the periphery of the masses in which they occur. Under certain conditions it is entirely conceivable, and even probable, that these basic secretions may acquire dimensions relatively great and be properly regarded as products of magma differentiation, as now understood, and yet have no connection with the periphery of the mass of the magma. Of such a character appear to be the areas of nepheline-pyroxene-malignite in the Poohbah Lake laccolite. The relative distribution of the other two types of malignite is not well known beyond the fact that the one prevails on the northern shores of the lake and the other on the southern. It is to be remarked, however, that, taking our orientation from the stratification of the Coutchiching rocks, the garnet-pyroxene-malignite is at the lower part of the mass and the amphibole-malignite at the upper part. From the further fact, however, that the laccolite mass has, as a solid rock, partaken of none of the disturbance, which has affected the Coutchiching series, it is probable that the latter was upturned prior to the invasion of the laccolite, so that our conceptions of the upper and the lower parts of the laccolite must be checked by this consideration.

The most striking fact which a review of the petrographical descriptions discloses is that intensely contrasted mineralogical, structural and textural variations are the concomitants of very moderate changes in chemical composition. This is well illustrated by a comparison of the analyses of the garnet-pyroxene-malignite and the amphibole-malignite.

	Garnet-pyroxene-malignite.	Amphibole malignite.	Difference.
SiO_2	51.88	51.38	+ .50
Al_2O_3	14.13	15.88	−1.75
Fe_2O_3 } FeO	7.39	5.85	+1.54
CaO	10.81	8.62	+2.19
MgO	3.44	4.43	− .99
Na_2O	6.72 } =11.29	7.57 } =11.77	− .85 } =.48
K_2O	4.57	4.20	+ .37
TiO_2	.33	.12	+ .21
P_2O_5	.96	.98	− .02
H_2O	.18	.42	− .24
Total	100.41	99.45	
Sp. g.	2.888		

Yet with these closely-allied chemical characteristics there are, as already pointed out, important mineralogical differences, the first rock containing an abundance of melanite and the second none; the first having much ægerine-augite and no amphibole, and the second much soda-amphibole and but a subordinate proportion of ægerine-augite. Again, the chemical differences between the garnet-pyroxene-malignite and the nepheline-pyroxene-malignite are not of a radical kind, yet one rock—that containing the smaller proportion of soda—is rich in nepheline, while the other has none. The rock containing the larger proportion of lime contains neither garnet nor plagioclase, while that with the less lime has considerable plagioclase and abundant garnet.

As regards structural variations, the most interesting point is that connected with the relative order of crystallization of the orthoclase in different types of the rock. In the nepheline-bearing rock it was clearly the last to crystallize, and forms a mesostasis in which other constituents are imbedded poikilitically. In the garnet-bearing rock quite the reverse is the case, since the bulk of the orthoclase is in the form of the huge porphyritic crystals imbedded in a paste of the other minerals. If we suppose that

in the two portions of the magma which resulted in the two types of structure the crystallization of the orthoclase was simultaneous, we have an explanation of this curious reversal of sequence of crystallization. If the more basic or nepheline-bearing facies of the laccolite be, as seems very probable, of earlier consolidation than the rest of the magma, the normal sequence of crystallization obtained, and the orthoclase crystallized last, forming a residual mesostasis. But if this portion of the laccolite were in free communication with the rest of it, as seems certain, crystallization may have been inaugurated throughout the latter about the time that the orthoclase was forming in the more basic portion. This local crystallization of the orthoclase may be assumed, for lack of a better hypothesis, to have set up, by a sort of sympathetic action, the general separation of the orthoclase, out of its time, throughout the entire laccolite.

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SIGMOGOMPHIUS LE CONTEI.

A

NEW CASTOROID RODENT

FROM THE

PLIOCENE NEAR BERKELEY, CALIFORNIA.

BY

JOHN C. MERRIAM.

CONTENTS.

OCCURRENCE.

THE fossil rodent remains here described and referred to the Castoridæ or beaver family, were found by the writer, about two years ago, near Bald Peak, two miles east of Berkeley. The fresh-water beds in which they were found form part of a very thick series of gravels, clays, limestones, and eruptives belonging, according to Prof. A. C. Lawson, to the lower division of the Pliocene.*

At the point where the rodent bones were found, the clays contain abundant but fragmentary organic remains, including shells of *Limnœa contracosta*, Cooper; *Planorbis pabloanus*, Cooper; *Anodonta Nuttaliana*, Lea var. *lignitica*, Cooper; *Cypris*, nov. sp.; *Ancylus* sp.; and *Helix* sp. Teeth of *Lepus* (?) and the dentary bone and

*The geology of the region in which these beds occur has been subjected to detailed study by Prof. A. C. Lawson, with the collaboration in part of Dr. Chas. Palache, and a monograph on the Pliocene rocks by these geologists is shortly to appear.

teeth of a lizard closely related to *Lacerta*, were also found in this stratum. In a semi-lignitic layer a short distance above that containing *Limnæa*, etc., numerous but imperfect plant remains* were found.

The rodent remains, consisting of the greater portion of a skull with the upper molars and incisors, were imbedded in a stratum of hardened clay immediately below the lignite.

Dr. Charles Palache was directly instrumental in the discovery of the skull, as the writer's first visit to the fresh-water beds was made under his guidance.

HISTORY OF THE CASTORIDÆ.

The beaver family reached its maximum development, in point of number of genera and species, in the middle Tertiary, and is represented at the present time by a single genus and species, *Castor fiber*, the beaver. The oldest representatives of the family known are found in the Lower Miocene, three species of the genus *Steneofiber* occurring at that horizon in America and one in Europe. This genus became extinct in the Middle Miocene of North America, but continues into the Upper Miocene and possibly Pliocene, *Steneofiber* (*Chalicomys*) *sigmodus* of Europe.

In the uppermost Miocene or lowest Pliocene (Loup Fork Beds) of North America two new genera, *Eucastor* and *Mylagaulus*, appear, representing new types of beaver, in which reduction in the number of molars has taken place. These types seem to have at least a distant relative in *Steneofiber* (*Chalicomys*) *sigmodus* of the European Pliocene.

The modern beaver, *Castor*, appears in the upper Pliocene of Europe and America, being accompanied in Europe by the genus *Trogontherium*, the largest representative of the family. *Castor* continues through the post-Pliocene up to the recent period, but its relative *Trogontherium* became extinct in the Quaternary. *Castor*

* These plant remains, though imperfect, could, in part, be determined by an expert in the palæobotany of the Coast Range Tertiaries. They may at some future time be of value in correlating the Pliocene of Berkeley with the more fossiliferous and better known Pliocene around Mt. Diablo. The latter contains, aside from a rich marine fauna, abundant plant material, which has been partially worked up.

fiber was formerly abundant in Europe and North America; it has, however, within comparatively recent times, suffered destruction through human agency to such an extent that its extinction is probably not far distant. In North America it was at one time found over the greater portion of the continent from northern Mexico as far north as the forest limit. It is now confined to the sparsely inhabited and less frequented districts. In Europe the present geographical distribution of the beaver is limited to a single locality on the river Elbe.

Most of the ancient Castoridæ were much smaller than the living form, averaging about half its size. The single exception is found in *Trogontherium*, which was somewhat larger than *Castor*.

In the following description, and in the discussion of affinities, it will be seen that the Californian Pliocene form bears an interesting relation to those from the Upper Miocene and the Pliocene of other portions of North America and Europe.

DESCRIPTION.

*Sigmogomphius Le Contei.**—*Gen. et sp. nov.* The posterior portion of the skull was unfortunately so decomposed and undistinguishable from the black, clayey matrix that in preparation only about one-half of the upper and two-thirds of the lower side could be made out. Evidently the greater portion of the skull was there originally, since the tympanic bullæ and other parts of the posterior end were present. The lower jaw could not be found.

The anterior half of the cranium, of which the superior aspect is shown in Fig. 1, *a*, resembles very much that of *Castor*, or perhaps still more the proportions of the bones in *Steneofiber*. The nasal region resembles that of the other Castoroid forms. The incisors are rather close to the upper molars. On the lower side the anterior palatine foramina appear to be largely, perhaps entirely, in the premaxillaries, but run back to the suture between maxillary and premaxillary.

The superior molar series Fig. 1, *b*, consisting of three semiprismatic teeth on each side, converge anteriorly as in most Castoridæ. As the number of molars is one of the important characters of the

*Named for Prof. Joseph Le Conte.

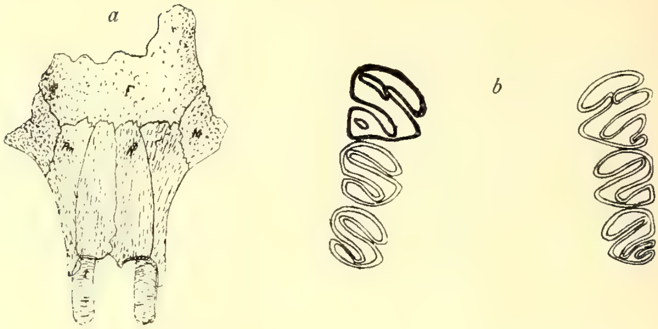

Figure i.—*Sigmogomphius Le Contei.* *a*, Skull, seen from above (natural size). F, frontal; N, nasal; Pm, premaxillary; M, maxillary; I, incisor. *b*, right and left superior molar series (twice natural size). Right premolar shown in section (heavy line) a short distance above the triturating surface.

genus, it should perhaps be stated that, although the head bones extend backward beyond the molars, no sign of a fourth tooth could be found on either side. The striking resemblance of the molars to those of *Eucastor*, Leidy, Fig. 2, *a*, which possibly possessed only three superior molar teeth, makes it appear the more probable that the fourth tooth was absent in *Sigmogomphius*. The molars were semi-hypselodont or semi-prismatic and strongly curved. They attained about half the size of those in *Castor fiber*, averaging near 11.5 mm. long; crowns, 4.8 mm. transversely, 4.5 mm. antero-posteriorly. Evidently they were not rooted till late in life, beginning to close up on the outer posterior corners, at which place a small lateral root was formed, the main portion continuing to grow for some time after this separation. The crowns of the premolars were larger than those of the molars, being about one-fourth longer and broader. Molars one and two were of nearly equal size. The triturating surface of the premolars is nearly triangular in outline; that of the molars is more nearly quadrate. All are set obliquely in the jaw, so that the folds of the enamel wall do not cut the fore-and-aft axis of the tooth at right angles, but obliquely.

The inner wall of all the molar teeth is thrown into a single strong fold, which, in the first tooth, traverses half the breadth of

the crown to meet a similar fold from the opposite side. In the second and third it crosses the triturating surface, touching or almost touching the exterior wall. The presence of the fold is marked on the inner side of the tooth by a strong, sharp groove reaching almost to the end of the larger root.

On the outer side one, two, or three folds may be present. The premolars have three, the first molar one, and the second molar in the right series one, in the left series two. Of the three folds present in the premolar the middle one is the strongest, reaching across the tooth to the inner wall. The anterior outer fold comes in contact with the inner loop about the middle of the triturating surface, and shows a decided thinning of the wall at the point of contact, so that the two folds have almost united to form a transverse lamella. The third, or posterior fold, occurring in the premolars and the second molar of the left side, is small but distinct. On molars one and two the large exterior fold present corresponds to the middle one of the premolar. In these two there seems to be nothing corresponding to the anterior outer fold of the premolar. In Fig. 1, *b*, the first molar tooth of the right side is shown in transverse section, one-fourth of the distance from the lower end. Here the anterior outer fold is seen to be an island, while the wall between it and the end of the inner fold is very thin. It seems possible that the island could unite with the distal end of the inner fold, giving it the length found in molars 1 and 2. The upper incisors, Fig. 1, *a*, were both present and differ little, if at all, from those of *Castor* or *Eucastor*.

COMPARISON WITH OTHER CASTOROID GENERA.

In comparing this specimen with the other genera of the Castoridæ, there is little in the bones of the skull, which have been found, to show its relations, though the palatal and nasal regions are rather more like *Steneofiber* than *Castor*. Characters of great comparative value are, however, found in the highly developed molars. The number of molar teeth, three, is evidently important, since the normal number for the Castoridæ is four. In *Mylagaulus*, Cope, there is an exception, reduction to three or two having taken place. In *Eucastor tortus*, Leidy, described from beds of nearly the

same age as the Berkeley Pliocene, there is found, perhaps, another exception. The specimen figured by Leidy,* Fig. 2, *a*, shows only three molars on each side, and in his description no reference is made to a fourth. The figure shows what is perhaps an alveole for a fourth tooth on the right side, but no mention is made of it in the text. The great reduction in size of the posterior molars would lead one to suppose that the third molar had disappeared in *Eucastor.* It is, however, true that in *Trogontherium*, Fig. 2, *c*, in which molars 1 and 2 are also much smaller than the premolar, a third molar, larger and more complex than the others, is present.

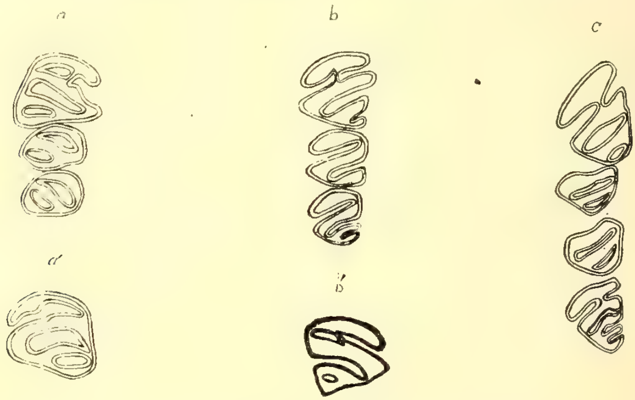

Figure 2.—*a*, Upper molar series, right side, of *Eucastor tortus; á*, left, upper premolar of the same (*a* and *á* twice natural size), after Leidy. *b*, upper molar series, left side, of *Sigmogomphius Le Contei; b′*, section of right upper premolar, cut a short distance above the triturating surface (*b* and *b′* twice natural size); *c*, left superior molar series of *Trogontherium Cuvieri* † (natural size), after Newton.

In number and arrangement of the enamel folds *Sigmogomphius* differs from *Castor* and *Steneofiber*, but approximates the characters in *Eucastor* and *Trogontherium.* In the first two genera there

*Extinct Mammals of Dakota and Nebraska, Pl. XXVI, Fig. 21.

† This figure was copied from an illustration, in which the enamel folds were indistinctly shown on the outer, right side. It was therefore impossible, in some cases, to tell whether the loops were closed or open at the outer end.

are always two or more enamel folds in the outer wall of the superior molars; in *Eucastor*, *Trogontherium*, and *Sigmogomphius*, the normal number for molars 1 and 2 is one. Both outer and inner folds are more oblique in these three forms than in *Castor* and *Steneofiber*.

Compared more particularly, Fig. 2, with *Trogontherium* and *Eucastor*, which are evidently its nearest relatives, *Sigmogomphius* differs from the first in having three molar teeth instead of four, in the more nearly quadrate form of molars 1 and 2, and in the open character of the folds, those of *Trogontherium* being in part closed up, forming islands. From *Eucastor* it differs again in possessing open folds, instead of the islands so characteristic of that genus. From both it differs in the relatively greater size of the molars. In *Trogontherium* and *Eucastor* the triturating surface of the premolar is nearly as long as that of molars 1 and 2 together, while in *Sigmogomphius* the length of the premolar as compared with that of molars 1 and 2 combined is about as one to one and a half.

From the above comparison it appears that the new form is more closely related to *Eucastor* and *Trogontherium* than to any other forms; also that the differences between it and these genera are too great to permit its reference to either one.

GEOLOGICAL AND GEOGRAPHICAL DISTRIBUTION OF THE CASTORIDÆ.

In the following table, giving the geological distribution of most of the known Castoroid species, the American Castoridæ seem to reach their maximum development at or before the beginning of Pliocene time. If the culmination of the group in Eurasia can be definitely located at all, it would seem to occur in the Pliocene, or somewhat later than in America. This seems the more probable, as the genus *Steneofiber* lived longer in Europe than in America, while of the three related genera, *Eucastor*, *Sigmogomphius*, and *Trogontherium*, the American forms became extinct long before the European.

The apparent earlier culmination of the American Castoridæ, together with the earlier extinction of certain forms in this country, seem to point toward the American rather than the European origin of the family.

<table>
<tr><th colspan="2"></th><th>EURASIA</th><th>NORTH AMERICA</th></tr>
<tr><td colspan="2">Recent</td><td>Castor fiber var. fiber</td><td>Castor fiber var. canadensis</td></tr>
<tr><td colspan="2">Quaternary</td><td>Castor fiber var. fiber
Trogontherium Cuvieri</td><td>Castor fiber var. canadensis</td></tr>
<tr><td rowspan="2">Pliocene</td><td>Upper</td><td>Castor issiodorensis
Trogontherium Cuvieri</td><td>Castor fiber var. canadensis</td></tr>
<tr><td>Lower</td><td>Steneofiber (Chalicomys) sigmodus.
Castor pelicedens (?)
Castor Rosinæ (?)</td><td rowspan="2">Sigmogomphius Le Contei
Eucastor tortus
Mylagaulus monodon
Mylagaulus sesquipedalis</td></tr>
<tr><td rowspan="3">Miocene</td><td>Upper</td><td>Steneofiber Jægeri</td></tr>
<tr><td>Middle</td><td>Steneofiber Jægeri
Steneofiber minutus</td><td>Steneofiber montanus
Steneofiber gradatus</td></tr>
<tr><td>Lower</td><td>Steneofiber eseri</td><td>Steneofiber nebrascensis
Steneofiber peninsulatus
Steneofiber pansus</td></tr>
<tr><td colspan="2">Eocene</td><td></td><td></td></tr>
</table>

Geological Laboratory,
University of California, February, 1896.

UNIVERSITY OF CALIFORNIA
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THE

GREAT VALLEY OF CALIFORNIA:

A CRITICISM OF THE THEORY OF ISOSTASY.

BY

F. LESLIE RANSOME.

CONTENTS.

INTRODUCTION.

THE following paper had its origin in a review of the literature bearing upon the theory of conservation of equilibrium in the earth's external form, which Dutton has named *Isostasy*, and which has come into prominence mainly through the labors of that illustrious group

of American geologists to whom geology is so deeply indebted for certain broad views and far-sighted generalizations, which in spirit and expression recall the wide regions and clear atmosphere in which their authors worked. The result of this review was to bring to the writer's attention many serious objections to the hypothesis as it has been held by probably the greater number of American geologists, and to cast doubt upon views in regard to sedimentation and subsidence which he had hitherto been rather disposed to entertain. It seemed desirable to eliminate this element of uncertainty as far as possible by the study of some particular area to which the theory of isostasy would seem to be applicable; and for this purpose the Great Valley of California is peculiarly fitted, in that it is an extensive area, possessing very definite boundaries, in which subsidence has apparently gone on step by step with sedimentary loading. It is, moreover, a physiographic feature of more than ordinary interest, which, as a whole, has never been made the subject of geological investigation. There are, it is true, many obstacles in the way of a complete discussion of the valley at the present time, owing to the imperfect knowledge possessed of certain portions of it, and the lack of any accurate map of the whole area. Accordingly the following discussion must be to a certain extent tentative, although it is believed that the information at present available is enough to serve as a basis of treatment, and it is hoped that with growing interest in physiography more attention will be given to the gathering of data bearing upon the later history of, on the whole, the most important physiographic feature of the state.

In the following pages it is proposed to give (1) a description of the Great Valley as it is to-day, (2) an outline of the geological evolution through which it has arrived at its present form, (3) an account of the development of the so-called "doctrine of isostasy" as a working hypothesis, (4) a discussion of the applicability of this hypothesis to the Great Valley, and (5) a more general discussion of the theory of isostasy, with illustrations drawn from other regions of elevation or subsidence.

PHYSIOGRAPHY OF THE GREAT VALLEY.

General Features and Subdivisions.—The Great Valley of Cali-

fornia lies, as is well known, between the two dominant mountain chains of the state,—the Sierra Nevada on the east and the Coast Ranges on the west. It has a length of about 400 miles, with an approximate average width of 50 miles, thus giving an area of 20,000 square miles, which is greater than the united area of the states of Vermont and New Hampshire. It forms a long and relatively narrow alluvial plain, in which the eye can rarely detect any departure from a monotonous level surface. The general trend of the valley is northwest and southeast, or parallel with all the main physiographic features of that portion of the state lying north of the 35th parallel of latitude. On any map of California, upon which the alluvial valleys of the more important streams are indicated by a separate color,* this general parallelism of mountain ranges, valleys, and coast-line is a very striking characteristic, and one to which there will be frequent occasion to refer.

As regards the natural features of drainage, the Great Valley is divided into three divisions of approximately equal lengths. The northern division, commonly known as the Sacramento Valley, drains southward through the Sacramento River, the middle division drains northward through the San Joaquin River, while the southern division has no regular drainage to the sea, the superfluous rainfall, and the water derived from the melting snows of the Sierra, being gathered into shallow lakes surrounded by broad, tule-covered swamps, and there evaporated. The largest of these is Tulare Lake, lying somewhat to the north and west of the middle of this southern portion. Although having no outlet, this lake is separated from the drainage system of the San Joaquin River by a gentle swell of alluvium, so slight, that in seasons of unusual freshets a transient connection is effected between the lake and the San Joaquin River on the north. The exact nature of this connection is rather obscure. According to Fremont,† the water from the lake flows northward into the San Joaquin River. Blake,‡ on the other hand, records

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*For example, the preliminary geological map issued by the California State Mining Bureau in 1891.

†Geographical Memoir upon Upper California, Washington, 1848.

‡Pacific R. R. Reports, Vol. V, p. 192. On page 144, however, Blake records a reported flow in the other direction, thus agreeing with Fremont.

that the water is said to flow from the latter river into the lake during high freshets. Prof. E. W. Hilgard informs the writer that the Kings River, which is tributary to the lake on the north through a plexus of mouths, sometimes sends a portion of its water northward to join the San Joaquin. All of this goes to show that the actual divide is very slight, and must lie somewhere between the San Joaquin River and the mouths of the Kings River. It is possible, too, that there may be no constant direction of flow, but that it may depend upon a rather delicate adjustment of the water carried by the two rivers, and upon the level of the lake, which is known tc be subject to considerable fluctuations.

The name San Joaquin Valley is frequently used to embrace not only that middle portion of the Great Valley drained by the San Joaquin River, but also the shallow basin in which Tulare Lake lies. It seems preferable, however, in view of the threefold natural division outlined above, to retain for the latter the name of Tulare Valley, as was done by Blake and the earlier explorers, while recognizing, as they did, that it is really a portion of the Great Valley separated, from the northern portions merely by an accident of drainage.

The whole Great Valley is completely walled in by mountains, except at one point, near latitude 38°, where the Sacramento and San Joaquin Rivers become confluent, and pour their united waters through the Straits of Carquinez into San Francisco Bay.

Having briefly sketched in outline the general features of the Great Valley, and indicated its convenient natural division into three parts, it will now be necessary to consider each of these sections in greater detail.

The Sacramento Valley.—The broad, flat, alluvial plain, having a width of about fifty miles near the point where the Sacramento and San Joaquin Rivers come together, gradually diminishes in breadth to the northward, and may be said to terminate near the town of Red Bluff, at an altitude of about 300 feet above the sea. For some 15 miles further north, however, the Sacramento River, with a grade increased to about 25 feet per mile, continues to be bordered by alluvial plains, which rise very gently toward the mountains on the west and east. This modern alluvium of the upper portion of the valley is evidently formed by the coalescence of the low alluvial

fans of the numerous streams which flow into the Sacramento River from the west, north, and east. Its upper limit varies somewhat, as would be expected. It appears to attain a maximum elevation of 1,300 feet* on the Cold Fork of Cottonwood Creek, on the west side of the valley, where it overlaps the old baselevel of erosion presently to be described.

On the east, the Sacramento Valley is bounded by the gentle slopes of the Sierra Nevada proper, until we reach latitude 39° 40′, approximately that of the town of Chico. Here the more ancient rocks of the Sierra begin to disappear under the late tertiary volcanic accumulations of the Lassen Peak volcanic ridge, which continues to form the boundary of the valley on its eastern and northeastern sides. Similarly on the west, the Coast Ranges proper give place as we go north, near latitude 40°, to the irregular and ill-defined group of little known mountains where the Coast Ranges and Cascade Ranges unite, and for which the name Klammath Mountains has been proposed.†

As regards the character of the slopes which the bounding mountain ranges present to the valley, it may be noted that whereas those on the west rise with comparative abruptness from the plain, the slopes of the Sierra, on the other hand, when we allow for the vigorous trenching of the present streams, rise toward the east with a remarkably regular and very moderate grade, and at their foot merge gradually into the plain. This long western slope has been emphasized by nearly every observer who has had occasion to describe the range as a whole. Newberry, indeed, says that "above Chico Creek the Sacramento Valley rapidly narrows, that portion lying east of the river forming a nearly level plain, four to six miles wide, from which the foot-hills of the Sierra rise abruptly."‡ But an inspection of the Chico topographic sheet of the U. S. Geological Survey hardly bears out his statement of abruptness, while immediately to the south of Chico Creek the gentle regular slope is very strikingly shown by the contours.

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*Diller, Topographic Revolution on the Pacific Coast. 14th An. Rept. U. S. Geol. Survey, p. 407.

†Diller, *loc. cit.*, p. 404.

‡Pacific R. R. Reports, Vol. VI, Geology, p. 25.

Diller* has described a well-marked plain of erosion bordering the upper portion of the Sacramento Valley. It is said to begin near the 40th parallel, on the west side of the valley, and to continue northward, bending eastward around the head of the valley to near the Great Bend of the Pitt River, where it passes beneath the lavas of the Lassen Peak district—a distance in all of about 100 miles. The width of the plain varies from 1 to 14 miles. On the west, this peneplain has been carved mainly upon the upturned edges of Cretaceous strata, but in a number of places "extends for several miles into the area of the harder and more durable metamorphic rocks of the Klammath Mountains." Its steepest average slope is less than two degrees, and its lower or easterly edge dips under the recent alluvium of the valley at elevations ranging from 600 to 1,300 feet, while the rear of the slope terminates against the Klammath Mountains at elevations from 1,100 to 2,600 feet. The transition of the peneplain into the mountain slopes at its rear is said to be sometimes abrupt and sometimes very gradual. It is believed to antedate the uplift of the Klammath Mountains, and to be still recognizable, within that group, in isolated tables up to 6,000 feet in elevation.

On the eastern side of the valley, the peneplain merges into, and becomes identical with, the general slope of the Sierra Nevada previously referred to. It is supposed to have been originally continuous with the level platform of the Interior or Basin Region. In the words of Mr. Diller, "The erosion plains that we have traced upon the borders of the Sacramento Valley, in the Klammath Mountains, upon the western slope of the Sierra Nevada, and probably also in the interior region of northeastern California, join one another in such a way as to show that they are parts of one extensive erosion plain which formerly spread over most, if not the whole, of middle and northern California and southern Oregon." The age of this baselevel is considered to be Miocene, and its formation regarded as being contemporaneous with the deposition of the Ione formation about its edges. The latter beds apparently never overlap the peneplain, and sometimes end abruptly against

**Loc. cit.*

a steep slope at its edge. They are accordingly of earlier or identical age with it, but not necessarily the latter, as Mr. Diller would have it. There is nothing in the evidence adduced that precludes a Pliocene age for the peneplain, and there are other facts which appear to indicate the latter as the true age.*

The almost horizontal strata on the west side of the valley, correlated with the Ione formation by Mr. Diller, consist of beds of gravel with some clay, with an observed maximum thickness of 64 feet. As the Ione formation was not found at the north end of the valley, no direct connection was observed between these beds and the typical Ione on the east side, and their reference to that horizon, without more evidence than is given, can be little more than a guess. If, indeed, they be a part of the Ione formation, and therefore probably, although not certainly, Miocene, then they are an exception to a general rule of structure early indicated by Whitney;† namely, that whereas on the eastern side of the Great Valley the rocks of Chico (Cretaceous) and later age lie almost undisturbed on the truncated older rocks, with a very slight westerly dip, the rocks of the Coast Ranges, up to and including the Pliocene, have been strongly folded. It must be said in this connection, however, that our knowledge of the geology of the immediate western edge of the Great Valley is as yet very imperfect, and that future investigation may reveal Pliocene, or even earlier, beds on the western edge which have escaped the vigorous folding to which their marine equivalents throughout the greater part of the Coast Ranges have been subjected. It is largely in consequence of this general rule of structure that the eastern slope of the Coast Ranges rises with some abruptness from the valley as contrasted with the western slope of the Sierra Nevada.

Conformably above the Ione formation in the northern part of the Sacramento Valley is the Tuscan formation, consisting principally of basaltic tuffs, and varying in thickness from 1,000 feet on the northeast side of the valley, to 50 feet or less along the western border. It is covered in turn by the unconsolidated deposits

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*See Professor Lawson, Bull. Dept. Geol. Univ. of Calif., Vol. 1, p. 271, and *ante*.

†Geology of California, Vol. I, p. 192.

called by Mr. Diller the Red Bluff formation, which fills up all the lower portions of this part of the valley.

The great alluvial plain proper of the Sacramento River, which may be said to begin near the town of Red Bluff, widens out rapidly to the south into the characteristic level expanse of the Great Valley, and the low rounded foothills recede on either hand. The only interruptions to this nearly level plain, stretching for over 300 miles to the southeast, are the Marysville Buttes, which emerge abruptly from the alluvium to a height of over 2,000 feet above the surface of the valley at about latitude 39° 15′, thirteen miles northwest of the town of Marysville. As can be seen from the Marysville Folio of the U. S. Geological Survey, they consist of a compact cluster of sharp peaks rising from an almost circular base of about ten miles in diameter. The highest point is 2,128 feet above sea-level. According to the work of Messrs. Lindgren and Turner,* they represent a volcano of rather remarkable type, consisting essentially of a core of massive andesite, surrounded by sediments and tuffs dipping away from it on all sides. These sediments have been identified as belonging to the Ione (Miocene?) and Tejon (Eocene) formations, which have a wide distribution about the borders of the valley, but have nowhere else been exposed in its middle portions. The age of the volcano was probably late Neocene. The base of the Buttes is undoubtedly deeply buried in the alluvium of the valley, from which they rise like islands from the sea. Borings in the tule-land, south of the Buttes, passed for 400 feet through unconsolidated deposits without reaching the beds which occur upturned upon their flanks.

The Sacramento River and its tributary, the Feather River, "pursue a winding course on low ridges,"† built up by the rivers themselves, as is common in streams meandering through a flood-plain. In the case of the Yuba River, which issues from the foot-hills of the Sierra to the east of Marysville, the amount of detritus run into the stream through mining operations has caused it to build up a low sandy alluvial fan upon which it shifts its course each season.

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* Marysville Folio, U. S. Geol. Survey.

† *Ibid.*

As a consequence of this, the town of Marysville, at an elevation of 66 feet above the sea, and formerly high and dry above the river, is now considerably below it at high water.*

The general drainage plan of the Sacramento Valley is comparatively simple. The Sacramento River follows a somewhat meandering course along the axis of the valley and is joined by numerous tributaries from the east and west. Those coming from the Sierra Nevada have generally a strong southerly deflection, flowing almost southwest, while those from the Coast Ranges flow in a general easterly direction. The broad western slope of the Sierra furnishes by far the larger part of the drainage and all of the important tributaries. The smaller streams flowing from the Coast Ranges on the west seldom reach the Sacramento River directly, but become lost in the intricate plexus of sloughs which meander through the tule-lands bordering the main river. The same is also true of the smaller streams on the east—only the larger tributaries reaching the Sacramento by a definite channel, and that often becoming an exceedingly tortuous one.

It is unfortunate that so few records of deep borings in the late sediments of the Sacramento Valley are known to the writer. Their depth is accordingly largely a matter of conjecture, except at such places on the edges of the valley as reveal the bottom in natural sections or by borings. Two wells are reported† to have been sunk, about 20 years ago, nine miles northeast of Sacramento, to depths of 2,250 and 1,600 feet, but there is apparently no record of the materials passed through. In the town of Sacramento, a well is described‡ which pierced unconsolidated clays, sands, and gravels to a depth of 965 feet. Lindgren and Turner,§ defining the alluvium as "the fluviate deposits of clays, sands, and gravels formed by the steady erosion of the older formations by the shifting streams since the Great Valley became dry land," give it a probable maximum thickness of 100 feet. As we shall see, however, in the description of the San Joaquin Valley, there is strong evidence that fluviatile deposits reach a vastly greater thickness than this in the middle por-

* Marysville Folio, U. S. Geol. Survey.
† Bull. 3 of the State Mining Bureau of California, p. 10.
‡ *Ibid.*
§ *Loc. cit.*

tions of the valley, and it seems impossible there to draw any natural line between the early Pleistocene and the alluvium, as the terms are used in the U. S. geological folios. For the purpose of this paper such distinction is not essential, and the term Pleistocene will be used to include all the unconsolidated deposits of presumably post-Tertiary age.

The San Joaquin Valley.—This valley, which has been described as draining northward through the San Joaquin River, resembles in a general way the Sacramento Valley, with which it is in direct continuation. Our information in regard to its western and eastern borders is, however, very meager. On the east, the low foot-hills are composed of flat-lying Tertiary sandstones, fine tuffs and clays, and gypseous beds, which rise very gradually out of the alluvium and lap up over the older truncated rocks of the Sierra Nevada in the long even slope already described. On the west, the Tertiary and Cretaceous sandstones and shales have been highly folded * and the slopes of the Coast Ranges emerge with comparative abruptness from the plain.

The general plan of the drainage resembles that of the Sacramento Valley, but the southerly deflection of the streams flowing down from the Sierra Nevada is not so great; in fact, as would be expected, they show slight northerly deflections when referred to lines perpendicular to the general northwest and southeast trend of the valley. Owing to the arid character of the eastern slope of the Coast Ranges, the predominance in volume of the drainage from the east over that from the west is much more marked than in the case of the Northern Valley, the western tributaries of the San Joaquin River being quite insignificant and practically lacking in its upper reaches. It is probably in consequence of this that the San Joaquin River, in its course along the valley, hugs closely the western side of the plain, and flows close under the base of the Coast Ranges, the building up of low confluent alluvial fans, by the rivers embouching on the plain from the Sierra Nevada, having forced the main San Joaquin River further and further west. The latter

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* Whitney Geology of California, pp. 55 and 188.

river itself, as it leaves the Sierra, continues its southwesterly course for more than two-thirds of the distance across the valley, before bending sharply to the northwest to take its way along the valley-axis.

The existence of natural gas beneath the city of Stockton, in the middle of the lower part of the San Joaquin Valley, has led to the prosecution of considerable deep boring, and has been productive of most interesting results. Some of these wells are over 2,000 feet deep, and one is reported to have reached a depth of 3,000 feet,* but in no case has the bottom of the unconsolidated fluviatile deposits been reached. The material passed through consists of fine sands and clays, with occasional beds of coarser sand and gravel. Logs of wood have been found up to 340 feet in depth, fresh-water shells belonging to living species at 600 feet,† and "sand, gravel and cobblestones" at 1,042 feet. There can be little doubt that these deposits indicate an actual subsidence of the valley floor at this point to an extent of at least 2,000 feet during Pleistocene times.

The Tulare Valley.—As already stated, this valley is separated from the San Joaquin Valley proper merely by a low alluvial divide at about latitude 36° 40′. It is the widest portion of the Great Valley, and, according to Blake,‡ is 70 miles wide by 150 long, and includes 7,500 square miles. It has no regular drainage to the sea, and it is doubtful whether the water from Tulare Lake itself ever finds its way into the San Joaquin River, although reported, by hearsay, to do so at certain seasons, by Blake and Fremont. This low divide has apparently been formed by the projection of alluvial fans of low angle into the valley by the San Joaquin and Kings Rivers. The latter river, after issuing from the foot-hills, curves to the south

* The information here made use of in regard to these wells is mainly taken from the Eighth, Tenth, and Twelfth Annual Reports of the State Mineralogist, 1888–1894.

† These shells were collected by Mr. W. S. T. Smith, and are now in the Museum of the University of California. The exact depth from which they were obtained is rather uncertain, resting upon the testimony of one of the workmen engaged in the boring.

‡ Pacific R. R. Reports, Vol. V, Geology, page 190.

and pursues a general southwest course toward Tulare Lake, whereas its normal course, as indicated by the parallelism of the other rivers entering the valley on this side, and by its own intramontane direction of flow, would take it close to the town of Fresno, several miles to the north of the present river. This town appears to be situated on a very low and sloping plateau, and it seems probable that the latter was built up by the Kings River, which has since shifted its course to the south onto a lower portion of its alluvial fan. Without much doubt it is this now deserted portion of the fan, assisted perhaps by that of the San Joaquin River on the north, which has dammed up the waters of Tulare Lake and prevented their free drainage northward.

This lake lies almost in the middle of the valley, but, like the main San Joaquin River, is nearer its western edge. It is described* as a very shallow body of water, surrounded, particularly on the north, east, and south, by broad tule swamps. Being so shallow, without outlet, and exposed alternately to the spring freshets from the melting snows of the Sierra Nevada and the desiccating winds of the hot summer months, it is subject to great fluctuations in area. According to Blake, "the greater part of the Tulare Valley was formerly submerged by a broad lake," and the region at present appears to be undergoing a gradual desiccation.†

The crowding over of the lake to the western edge of the valley is plainly due to the encroachment of the beautifully symmetrical fan of the Kaweah River, assisted by the deltas of the Kings River on the north and of the smaller streams to the south. A similar case of displacement can be seen in the extreme southern end of the Tulare Valley, where the two small lakes of Buena Vista and Kern owe their present positions to the westward growth of the large delta of the Kern River.

The relation of Tulare Valley to its surrounding mountains is graphically described by Whitney‡ as follows: "The mountains close entirely around the end of the great plain of the San Joaquin

* Pacific R. R. Reports, Vol. V, Geology, p. 193.

† *Ibid.*

‡ Geology of California, p. 187.

and its continuation in the Tulare Valley, forming a vast amphitheatre, unbroken on all sides except to the north, but lowest to the west at Paso Robles. The mountains south and east are especially high, rising to from 6,500 to 8,000 feet. From the base of these a dry, gravelly or sandy slope stretches away with a very gentle inclination into the plain; this is composed of coarser materials, and has a steep angle near the mountains, gradually becoming more nearly horizontal as it recedes from them. This detrital deposit covers the base of the mountains to the height of 1,000 feet above the plain, and is made up of the materials brought down the slopes of the mountains by the wear of the elements. Near the mouths of the cañons which issue from the hills there are accumulations of boulders, which are also scattered over the plain to some extent, around and near the base of the hills."

According to the same writer, the line of division between the Sierra Nevada and the Coast Ranges occurs somewhere between Tejon Cañon on the east, and the Cañada de las Uvas on the west, the Tertiary strata at the former place having the nearly horizontal position characteristic of the Sierra, while at the latter the rocks of the same age are highly tilted, as is commonly the case in the Coast Ranges.* Mr. H. W. Turner† has suggested that the line between the disturbed and undisturbed strata is really a fault, whose northern prolongation determines the course of the San Joaquin and Sacramento Rivers. There is nothing in the drainage, however, to support the suggestion, for a river which meanders over a flood-plain, in a broad valley, deeply filled with alluvium, can hardly be supposed to have any necessary connection with an underlying fault. An idea of the depth of the Pleistocene deposits in Tulare Valley is given by a well-boring near Tulare Lake which passed through sands and clays to a depth of 1,058 feet. Fresh-water shells belonging to living species are reported from this depth.‡

THE HISTORY OF THE GREAT VALLEY.

In any attempt to trace the geological evolution of the Great

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**Loc. cit., p. 192.*

†Am. Geologist, Vol. XIII, p. 248; also Journal of Geology, Vol. III, p. 386.

‡Watts, Gas and Petroleum Yielding Formations, Bull. 3, Calif. State Mining Bureau, p. 20.

Valley to its present form, our present imperfect knowledge of the geology of its bounding mountain ranges, more especially of the eastern portions of the Coast Ranges and Klammath Mountains, is a serious obstacle. It is very doubtful whether anything at all comparable with the present valley existed during Cretaceous times. According to Mr. Diller,* the Klammath Mountains formed an island during the early part of this period at least, but our knowledge of these mountains is too slight for anything like a positive statement to be made. At Paskenta, on the west side of the Sacramento Valley, there is a great thickness of Cretaceous strata exposed, dipping steeply toward the valley. Mr. Diller, referring to these strata, speaks of over 29,000 feet of sediments (Shasta-Chico Series) being laid down in the Sacramento Valley, but he probably hardly means to convey the impression that there was then any distinct valley. No such thickness of Cretaceous rocks is found on the eastern or Sierra Nevada side of the valley, and we should rather suppose that the sediments observed at Paskenta thin out under the present valley, and that their greatest thickness, and therefore the deepest depression in which the Cretaceous sedimentary lens was deposited, was either at the above-named place, or even at some place west of it, over the site of the present Coast Ranges. In the latter case the strata have probably been largely removed by denudation. Throughout the Coast Ranges the Cretaceous strata are so widely spread, and so considerable in volume, as to indicate that the region occupied by these mountains was not only submerged at that time, but was probably more deeply submerged than was the area of the present Great Valley.

During the Eocene (Tejon), according to Mr. Diller,† northern California and a large part of Oregon were above sea and being degraded, no Eocene deposits being known in California above the 40th parallel. There was probably a gradual subsidence, as shown by the thinning out of the Tejon northward in California. But so much being granted, there is nothing to indicate that any step had been taken toward the initiation of the Upper Sacramento Valley,

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**Loc. cit.*, p. 423.

†Topographic Revolution on the Pacific Coast, 14th An. Rept. U. S. Geol. Survey, p. 424.

while to the south of the 40th parallel the probabilities are that the sea had an almost, or wholly, unbroken sweep across the area now occupied by the Coast Ranges and the Great Valley.

"The Miocene," says Mr. Diller, "was initiated with no marked change of level in Northern California unless a subsidence."* The great development of marine Miocene throughout the Coast Ranges, and its occurrence on the west slope of the Sierra Nevada at Ocoya Creek,† and also at the Marysville Buttes,‡ would indicate that the sea had free access to the Sierra Nevada across the site of the Coast Ranges, and over the greater part of the area now occupied by the Great Valley. On the other hand, the brackish-water character of the (supposedly Miocene) Ione formation would indicate the existence of some barrier between the northern and middle portions of the Sierra, and the open sea to the west. Of course if the peneplain described by Mr. Diller be of Miocene age, then there was a very definite land barrier to the west of the present upper Sacramento Valley; but it seems almost incredible that, during the folding and elevation of the great Miocene sediments throughout the Coast Ranges, and the upheaval of the Klammath Mountains by several thousands of feet, that a strip of peneplain should still be preserved about the western borders of the upper Sacramento Valley, which has suffered little change beyond being gashed by the cañons of the modern streams, and is still an easily-recognized feature in the topography.

Lastly, the age of the brackish-water Ione formation is still a somewhat unsettled question, and this should be borne in mind when drawing conclusions as to the physical geography during Miocene times. It is possible that with further knowledge of the mountain ranges inclosing the Great Valley we may be able to trace in Miocene times the first faint boundaries of the whole or a part of the valley as known to us to-day, but at the present time we must agree substantially with Antisell§ in considering that "probably during the whole of the Miocene the Coast Range was

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* *Loc. cit.*

† Blake, Pac. R. R. Reports, Vol. V, Geology, p. 164. Also Whitney, Geol. of Calif., p. 201.

‡ Marysville Folio, U. S. Geol. Survey.

§ Pacific R. R. Reports, Vol. VII, Geology, p. 19.

altogether beneath the sea-level," and take up its history at a point subsequent to that time.

The occurrence of a great orogenic disturbance at the close of the Miocene, giving birth to the Coast Ranges as a connected mountain chain, appears to be one of the best established facts in the geology of California. From that disturbance dates the history of the Great Valley. During Pliocene times the Coast Ranges, although depressed from 800 to 2,100 feet below their present level,* still persisted as a more or less continuous land barrier, as shown by the development of extensive peneplains with accompanying delta-formations, and the local accumulation of great thicknesses of littoral Pliocene sediments which rest unconformably upon the Miocene.

According to the U. S. Geological Survey,† the Great Valley was probably occupied during the whole of the Neocene by a gulf, connecting with the ocean by one or more sounds across the Coast Ranges,—which is in general harmony with the foregoing. As yet, however, we can say very little about Pliocene sediments in the Great Valley. The geologists of the Geological Survey, working on the northern and eastern portions of the valley, have found it impracticable to subdivide the Neocene, and in general, it may be said that we are without any authoritative information concerning marine Pliocene deposits within the Great Valley, although they are found at Kirker's Pass, high up on its western rim.‡ Their apparent absence would indicate that the western barrier was either more continuous than would appear to be the case from a study of the Coast Ranges themselves, or that the present floor of the valley was above sea-level, in which case it must have been a gently sloping plain rather than a valley, or, lastly, the rivers draining the land to the east may have been so augmented in flow as to prevent, by the influx of a large volume of fresh water and the deposition of gravels in their turbulent currents, the laying down of sediments bearing marine organisms. It is probable that no one of these three alternatives obtained to the exclusion of the other two. In spite of

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* Lawson, Bull. Dept. Geol. Univ. Calif., Vol. I, pp. 157 and 270.

† Description of the Gold Belt, Jackson Folio, etc., U. S. Geol. Survey.

‡ Turner, Geology of Mt. Diablo, Bull. Geol. Soc. Am., Vol. II, p. 396, with references to Whitney and Gabb.

the heavy local accumulation of marine Pliocene in the Coast Ranges, it is likely that by far the greater part of the latter was above or very close to sea-level. During the Pliocene, with the Coast Ranges thus depressed, and the present site of the Sierra Nevada occupied by a peneplain of much gentler slope than now, the bottom of the Great Valley stood at a relatively greater elevation than at present, with reference to its inclosing rim, and may have been partly above the sea-level, and certainly could not have been far below it. We know, too, that during the latter part of the Pliocene, the rivers flowing down over the Sierra Nevada peneplain, were actively engaged in depositing gravels along their lower courses.

Finally, at the close of the Pliocene, occurred the oft-described elevation of the Sierra Nevada by a tilting of the old peneplain towards the west (*i. e.*, towards the Great Valley), and closely following it the gradual emergence of the Coast Ranges, which has continued through the Pleistocene to the present time, as ably shown by Professor Lawson. The obvious effect of this double uplift, along two nearly parallel axes, was to deepen the Great Valley, and give it substantially its present form. To quote from Professor Lawson, "Numerous islands, large and small, fringed the coast of California. There were numerous submerged valleys, so that the coast was well supplied with harbors. In a word, the coast of California at the close of the Pliocene, had the aspect of an archipelago. The archipelagic condition endured into the early Pleistocene, and from this condition it has been gradually recovering up to the present day."* An exception to this recovery was noted by the same writer in a later paper, however, in which it is shown that a local subsidence to the extent of 378 feet, and "entirely subsequent to the general uplift of the coast," has affected the region of San Francisco Bay.†

It will be seen from the foregoing, that up to the beginning of the Pleistocene, the area now occupied by the Great Valley was at no time the theater of particularly heavy sedimentation or active subsidence. There is evidence that during the Cretaceous and Miocene the heaviest sediments and deepest depressions lay to the

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* *Loc. cit.*, pp. 158, 159.

† *Ibid*, p. 265.

west of the present valley, and along the line now occupied by the Coast Ranges. During the post-Miocene upheaval of the latter, the folding, as is generally the case, was confined to the zone of exceptionally thick sediments, while the floor of the Great Valley seems to have remained as a passive, inert mass between the folding Coast Ranges and the Sierra Nevada. Such subsidence as it may have experienced during these periods would be but a marginal facies, as it were, and directly dependent upon the far greater subsidence which allowed the heavy accumulations to take place which were subsequently folded up into the Coast Ranges. It is therefore a corollary to the problem of the formation of these ranges, and of mountain building in general, which, although it may be regarded as an isostatic problem, is not the particular one with which we are immediately concerned.

But with the post-Pliocene elevation of the crest of the Sierra, and with the gradual upward diastrophic movement of the Coast Ranges during Pleistocene times, whereby the Great Valley was finally cut off from the sea, we are brought directly to the problem in hand. The valley became closed in by mountains as we find it at the present day, and became a definite and well-bounded area of sedimentation or deposit. The movements which brought about this condition are, as far as we know, still going on. The great orographic block of the Sierra Nevada is still being tilted up at a higher angle, and the Coast Ranges (with perhaps one or more local exceptions) are still emerging from the sea. All through Pleistocene and recent times, the streams flowing down from the Sierra, and from the eastern slope of the Coast Ranges, have been pouring detritus into the deepening valley, depositing the coarser materials in broad alluvial fans, and carrying the finer silt farther out, to be spread over the plain in flood seasons. We have seen that at Stockton, in the middle of the valley, borings to a depth of from 2,000 to 3,000 feet remain entirely within unconsolidated fluviatile deposits. The age of all these clays, sands, and gravels is not definitely known, but it seems most probable that they are all post-Miocene, or even post-Pliocene. There is nothing, unless it be their great thickness, which points to any but a very recent geological age for the deposits, as far as they have been penetrated by borings. With the present sur-

face of the ground only 46 feet above sea-level, the occurrence of logs of wood at 340 feet, recent shells up to 600 feet, and coarse gravels at depths of over 2,000 feet, can only be accounted for upon the supposition of an equal subsidence. Numerous beds of coarse gravel could have been deposited in the middle of this broad valley only when its bottom was close to, or above, sea-level. If, as supposed by the geologists of the U. S. Geological Survey, the Great Valley was occupied by a shallow lake during early Pleistocene times, then the fluviatile deposits under Stockton would seem to be of even later date. But probably then, as now, the valley was mainly above sea-level. The streams flowing into it may have formed local and transient lakes through the damming up of the drainage by delta-formations, as is seen in the case of Tulare Lake to-day. During the wet seasons, extensive floods probably spread the finer materials widely over the floor of the valley, as is done on a smaller scale by the existing rivers. There is the possibility, too, that the elevation of the Coast Ranges may have been at times more rapid than the corrasion of the outlet of the valley at Carquinez Straits, thus leading to a temporary, but more or less general, flooding of the Great Valley with fresh water.

Finally, the subsidence in the middle of the Great Valley, as shown by borings, is not to be considered alone, but evidently stands in some connection with the more extensive local sag in which the Bay of San Francisco lies, and which has been described by Antisell* and Lawson.† To sum up briefly, we have during Pleistocene times a progressive general elevation of the rim of the basin in which the Great Valley lies, first by the tilting of the Sierra Nevada crustal block, and second by the epeirogenic uplift of the Coast Ranges as a whole. At the same time, sediments are being deposited in the valley aggregating over 2,000 feet in thickness in its middle portion, with an accompanying *pari passu* subsidence or depression of the valley floor. Coeval with this subsidence we have a marked sag across the Coast Ranges in the same latitude, resulting in the flooding of San Francisco Bay.

The Great Valley is an example of a well-defined area of pro-

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* *Loc. cit.*, p. 27.

† *Loc. cit.*, p. 265.

gressive subsidence associated with heavy accumulations of sediment. The persistency of a similar association between subsidence and sedimentation has long been recognized, and two diametrically opposed views have been, and still are, held in regard to it. According to the one, long-continued and heavy deposition can only take place concurrently with, and in consequence of, subsidence of the area receiving the sediment, and elevation of the area denuded. It is this movement which disturbs the previously existing equilibrium and sets in motion the forces of erosion, transportation and deposition. Those holding this view may or may not commit themselves to any discussion of the rigidity of the earth's crust, but the greater number of them assume that it is possessed of sufficient rigidity to be unaffected by the transference of material from one area to another by the ordinary processes of sedimentary transportation. In contrast with this older view, which is simply a condensed expression of the first principles of dynamic geology as taught by Lyell, there has of late years been advanced by very able geologists, particularly in America, the so-called "doctrine" of isostasy, in accordance with which loading by sedimentation is looked upon as the active cause of subsidence, and lightening by erosion as the immediate cause of elevation. The avidity with which this doctrine has been accepted in the United States, and to a less extent in Britain, taken in connection with the slight amount of effective protest from those holding the other view, is rather remarkable; and we are treated to the somewhat unusual spectacle of two opposite, although not necessarily wholly contradictory, theories, existing amicably side by side. Before proceeding to the application of either of these opposing theories to the particular case under consideration, it will be well to consider in a general way the development of the theory of isostasy as applied to areas of subsidence receiving sediment.

DEVELOPMENT OF THE THEORY OF ISOSTASY.

With the impetus given by Lyell to the inductive method in geological investigation, it was not long before various observers noted the now well-established fact, that great deposition of sediment has been attended by a more or less gradual subsidence.

This association of deposition and subsidence, discerned at a time when our conceptions regarding the interior of the earth were, if less vague, more primitive than at present, and when the commonly accepted theory of the earth was that of a thin crust floating upon a molten interior magma, led easily to the explanation brought forward by Herschell,* Babbage,† and Hopkins,‡ that the subsidence was due to a bending downward of the thin crust under the load, and a consequent displacement of the sub-crustal magma. The latter would then most naturally flow under that adjoining portion of the crust relieved of weight by denudation, and cause it to rise.

When the vast sedimentary accumulations of the United States began to be carefully studied, the same association of deposition and subsidence was even more strikingly shown and on a grander scale. Hall § in 1859 showed that the sediments, over 40,000 feet in thickness, which were laid down over the site of the present Appalachian region, are all of shallow-water origin, and must have been deposited on a gradually subsiding sea-bottom. He regarded this subsidence as the result of the loading.

King ‖ arrived at a similar conclusion in regard to the still greater Palæozoic sediments of the western territories.

Dutton,¶ in 1879, in a preliminary paper on the Colorado River and plateaus, pointed out that "those areas which have been uplifted most have been most denuded," and says that he has "asked himself a hundred times whether we might not turn this statement around and say that those regions which have suffered the greatest amount of denudation have been elevated most, thereby assuming the removal of the strata as a cause and the uplifting as an effect. . . . Few geologists," he goes on to say, "question that great masses of sedimentary deposits displace the earth beneath them and subside. Surely the inverse aspect of the problem is *á priori*

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* London and Edinb. Philos. Mag., Vol XI (1837), p. 212.

† Q. J. G. S., Vol. 3, p. 186.

‡ Brit. Assoc. Rept. 1847, p. 73.

§ Palæontology of N. Y., Introd. to Vol. III, p. 69, *et. seq.*

‖ Exploration of the 40th Par., Vol. I, p. 732.

¶ Geolog. Hist. of the Colorado River and Plateaus, Nature, Vol. XIX, pp. 247–252 and 272–275.

equally palpable." Dutton, while inclined to regard denudation and deposit as the active causes of elevation and subsidence respectively, nevertheless realizes the necessity of appealing to something else to *initiate* the differential movement, namely, "that mysterious plutonic force which seems to have been always at work and whose operations constitute the darkest and most momentous problem of dynamical geology." In the following year he states that in the plateau region of Utah sediments from 6,000 to 15,000 feet in thickness have been deposited over an area of more than 100,000 square miles, and reveal the fact that at no time was the upper stratum far from sea-level. The strata sank as they were deposited. It is suggested that the displaced sub-crustal magma flowed under the rising Wasatch and Uinta Mountains and beneath the Great Basin.*

The theory of the earth's crust so ably expounded by the Rev. Osmond Fisher is now too well known to require any recapitulation here. It is enough to say that it is closely bound up with the hypothesis of a sensitive crust rising and sinking under varying loads, and has undoubtedly been influential in giving prominence to that view. He says in brief: "The exciting cause of the movements of the crust, as we have attempted to explain them, is the transference of sediment. Wherever that goes on, movements of the crust may be expected to take place. And, although not altogether confined to these regions, it is obvious that in continental areas, and along their shores, these processes are the more energetic."†

It is interesting, in view of the manner in which geologists have been content simply to hold opposite theories on this question, to compare Dutton's general statement in 1879, as to the consensus of geological opinion in regard to subsiding sedimentary tracts, with one made by W. O. Crosby,‡ only four years later, in which he says, "Geologists do not now generally believe that the profound subsidences permitting the deposition of thick sedimentary formations are produced by these same sediments." Truly a remarkable revolution of general opinion, for which, however, we have no further evidence than the two opposing statements themselves.

* Geol. High Plateaus of Utah, Washington, 1880, p. 13.

† Physics of the Earth's Crust (1881), pp. 221, 222.

‡ Origin of Continents, Geolog. Mag., Vol. XX, pp. 244, 245.

In the middle of the same year (1883) a paper appeared in England by Dr. Ricketts,* in which he calls attention to the lack of interest taken in the question whether sedimentation is the cause of subsidence or *vice versa*, and refers to an earlier paper published in 1872.† He favors the former view, but brings little to its support.

A month later Gardner ‡ published a paper in "Nature," in which he also regards the earth's crust as being highly sensitive to superficial loading, as shown by the subsidence of delta-deposits in particular. He also gives considerable prominence to the supposed effect of pressure in producing a fusion and viscosity of the deeply buried lower beds.

This paper was the immediate cause of a considerable correspondence on the subject in the pages of "Nature" during this and the following year, which, although of a rather desultory character, brought out a few points which may be worth noting in this place. Mackie § points out that if subsidence be due to loading of sediment, then it should continue indefinitely. He considers that it is due to tangential pressure acting upon a portion of the crust that has been thickened by sediment and thereby rendered more resistant. The area of deposition becomes a geosyncline. Gardner || carries the idea of a sensitive crust so far as to believe that the removal of weight by erosion along a sea-cliff causes a local elevation which results in giving the strata exposed in the cliff a prevailing landward dip. Ricketts ¶ suggests that the height of ordinary hills may be largely due to lightening through denudation. Sington†† is opposed to such views of a sensitive crust, and says that "every formation appears to contain evidence that subsidence took place independently of deposition, and elevation independently of denudation." He cites the case in which 5,000 feet of limestone is succeeded by grits and shales in Derbyshire, indicating a rise of the sea bottom pre-

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*Oscillations of the Earth's Crust, Geolog. Mag., Vol. XX, p. 302.

† Geol. Mag., Vol. XIX, p. 119.

‡ Elevations and Subsidences: Or the Permanence of Oceans and Continents. Nature, Vol. XXVIII, pp. 323–327.

§ *Ibid*, p. 488.

|| *Ibid*, pp. 488, 489.

¶ *Ibid*, pp. 539, 540.

†† *Ibid*, p. 587.

ceding the deposition of the latter, and asks whether we are to consider the three beds of sediment which often succeed a layer of coal in the coal measures as being sufficient to cause the subsidence that certainly took place during their deposition. Gardner * states that the depression of the earth's crust by sediments, and the elevation of the same on the removal of weight, are facts which can not be disproved. He recapitulates the original idea of Herschell of the displacement of the subcrustal magma by the addition of sediments to the crust above it. Lastly, Professor Le Conte † recalls a paper read by himself in 1859, before the American Association, in which the continents are regarded as floating upon an interior liquid magma and rising higher as lightened by erosion. His position in 1884 is summed up in the following sentence: "That loading and unloading the crust is a cause of subsidence and elevation there is little doubt, but that there are others and far more important causes is certain."

Dutton,‡ in 1884, emphasizes the enormous bulk of Mauna Loa, and states that the whole mass has been rising while lavas have been piling up. He suggests that regional elevation and volcanic action are probably due to the same cause. The former is caused directly by an expansion or by an increase of mass—probably the former. Mauna Loa "floats high" because it is light, the upper part being spongy and the lower part hot.

In his "Origin of Mountains," published in 1886, Reade says that "bendings of the earth's crust initiated in other ways may be increased by loading, but that the crust responds in a perceptible way to every additional foot of strata laid down upon it is too great a refinement to be possible."§ He conceives that the piling up of ten miles of sediment might displace those benenth by flowage under the enormous pressure, and refers to a probable connection between sedimentation, subsidence, and earthquakes. As opposed to unloading being the cause of elevation, he cites the well-known fact "that the whole of an elevated region eventually gets leveled

* *Ibid*, pp. 587, 588.

† *Ibid*, Vol. XXIX, pp. 212, 213.

‡ Hawaiian Volcanoes, 4th An. Rept. U. S. Geol. Surv., pp. 190–195.

§ Origin of Mountains, p. 272.

down approximately to a plane, and that it does not, after a certain period, continue to rise higher and higher above the sea-level, as the theory of elevation and subsidence by loading and lightening would seem to demand."*

In the same year Professor Le Conte,† speaking of the causes of elevations and subsidences of portions of the earth's crust, presented the most incisive protest against the adoption of the unmodified theory of equilibrium that had yet appeared, and the passage is here quoted in full. He says that "in these later times there has been a tendency to regard elevation and subsidence, when unattended by plication, as a simple matter of equilibrium of a floating crust. According to this view, wherever abundant sedimentation is going on, there the crust, weighted down by the increasing mass, subsides *pari passu*, and wherever erosion is exceptionally active, as in great mountains and high plateaus, there the ever-lightening crust rises *pari passu*. Thus subsidence and elevation are caused by weighting and lightening. Doubtless this is a real cause which must not be neglected, but it can not be the principal cause. Doubtless the proposition is true, but the converse proposition is much more true, viz.: that subsidence is the cause and necessary condition of sedimentation, and elevation the cause of exceptional erosion. The plateau region, for example, during the Carboniferous, Permian, and whole Mesozoic times, was a region of subsidence to the extent of 15,000 feet (for such is the thickness of the strata there). Since that time it has been a region of elevation, and has risen, probably, at least 20,000 feet. But the extreme *general* erosion (*i. e.*, leaving out the cañon-cutting) has been only about 12,000 feet, leaving the region still 8,000 feet high in its highest parts. Now, first, why did the rise commence at all? and, second, how can a lightening by removal of 12,000 feet cause an elevation of 20,000 feet? In fact, at every step the erosion has lagged behind the elevation, as it ought, if it be effect. The fundamental cause of subsidence and elevation over large areas must therefore be sought elsewhere, although, doubtless, weighting and lightening, by adding to the

* *Loc. cit.*, p. 297.

† The Elevation of the Sierra Nevada, Am. Jour. Sci., Vol CXXXII, pp. 167–181.

force or lessening the resistance, will cause these movements to go farther than they otherwise would. This is but an example of reaction of effect on cause, of which we find so many in all cases of complexly related phenomena. As to the real and fundamental cause of the oscillatory crust movements we are not yet prepared to speak with any certainty. We must wait for more light."*

McGee, in 1888,† refers to subsidence by loading, but says that it is a process which would soon run down were there not other forces active to revive it.

Prof. Lloyd Morgan,‡ in the same year, suggested a rather novel view of the cause of subsidence of the earth's crust under a load of sediments. He supposed that the weight of the latter might solidify a portion of the underlying fluid magma which would then contract and allow a certain subsidence to take place. Furthermore, the solidified portion, by sticking to the bottom of the crust, would tend to increase the weight and carry the process further. Where it would finally stop we are not told.

Ricketts, in 1889,§ argues that subsidence is due to loading by sediments, but the most interesting thing in his paper is a foot-note, in which he states that he has seen at least ten instances where the Carboniferous limestone, during the period of its formation, had been locally raised above sea-level and eroded. In eight of the examples thin beds of coal were found on the eroded surface, sometimes separated by clay. Just how this evidence supports his general contention is not by any means clear, while it certainly is very welcome to those opposed to it.

In 1889, Dutton || conferred a great service upon the hypothesis first advanced by Herschell, by casting it in a more comprehensive and clear-cut statement than had been done hitherto, and by proposing the word *isostasy* to express that "condition of equilibrium of

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* *Loc. cit.*, p. 180.

† Some Definitions in Dynamical Geology, Geol. Mag., Vol. XXV (1888), p. 493.

‡ Geol. Mag., Vol. XXV (1888), p. 291.

§ On Some Physical Changes in the Earth's Crust, Geol. Mag., Vol. XXVI, p. 47.

|| On Some of the Greater Problems of Physical Geology, Bull. Philos. Soc. Wash., Vol. XI, pp. 51–64.

figure to which gravitation tends to reduce a planetary body, irrespective of whether it be homogeneous or not." But within this broad statement there are really two problems involved,—one pertaining to the department of mathematical physics, and one to that of observational geology, although the two, as is usual in such cases, show a certain amount of overlapping. Few geologists will be disposed to deny that great changes in relative density, or the transference of relatively large masses from one portion of the spheroid to another, would disturb the existing isostasy and lead to some modification of the form of the spheroid, whatever strong views they may hold as to the earth's rigidity under ordinary circumstances. The question which immediately concerns the geologist, however, is whether there is anything, in the past history or present condition of the earth's surface, that can lead us to suppose that any such isostatic adjustment need be taken cognizance of in dealing with purely geological phenomena. Among the latter there are no processes through which more stupendous shiftings of material from one portion of the earth's surface to another are effected, than those which are embraced in the terms denudation, transportation, and deposit or sedimentation, and the isostatic problem, for the geologist, may be considered as practically narrowed down to the single question of whether this transfer of material has any applicable effect upon the solid crust* of the earth. Can we regard it as sinking under and because of the added load, and rising because it is lightened by erosion, or must we look upon it as a floor whose movements take place independently of such superficial transferences of material.

Woodward,† in the same year, sums up the case for and against isostasy as follows: "As yet we can see only that isostasy is an efficient cause if once set in action; but how it is started and to what extent it is adequate remains to be determined. Moreover,

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*In using the term "crust" for the solid external portion of the spheroid, the writer nowhere means to imply that there is any sharply defined shell, definitely separated from an interior portion of different character.

†Mathematical Theories of the Earth, Am. Jour. Sci., 3 ser., Vol. XXXVIII, p. 351; also Science, N. S., Vol. I, p. 194; Trans. N. Y. Acad. Sci., Vol. XIV, p. 73.

isostasy does not seem to meet the requirements of geological continuity, for it tends rapidly towards stable equilibrium, and the crust ought therefore to reach a state of repose early in geologic time. But there is no evidence that such a state has been attained, and but little if any evidence of diminished activity in crustal movements during recent geologic time. Hence we infer that isostasy is competent only on the supposition that it is kept in action by some other cause tending constantly to disturb the equilibrium which would otherwise result. Such a cause is found in secular contraction, and it is not improbable that these two seemingly divergent theories are really supplementary." *

It is evident that he here has reference to that aspect of the problem which has just been called the geologic side. It is not quite clear, without further statement, why isostasy should rapidly tend to stable equilibrium, unless we assume that there is a limit to the progressive elevation of a region which is being worn down by erosion. The idea of such a limit is not in itself opposed to the theory of isostasy, as Reade and others have thought; for it is quite conceivable that such an elevation would result in bringing deeper and denser portions of the crust closer to the surface, whereby the tendency to rise would finally be accurately counterbalanced. Granting some such explanation as this, it is then evident that the land would all be permanently reduced to sea-level, as the theory of isostasy is inadequate to account for any new rise of land when all has been degraded to that plane.

Gilbert,† also in 1889, from a study of the up-arching of the central part of the desiccated Bonneville basin, reaches the conclusion that 600 cubic miles' concavity or protuberance may be taken as the measure of the crust's rigidity. He formulates, as a working hypothesis, the following: "Mountains, mountain ranges, and valleys of magnitude equivalent to mountains, exist generally in virtue of the rigidity of the earth's crust; continents, continental plateaux, and oceanic basins exist in virtue of isostatic equilibrium in a crust heterogeneous as to density."

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* *Loc. cit.*, p. 352.

† Strength of the Earth's Crust, Bull. Geol. Soc. Am., Vol. I, p. 23–27; also Monog. I, U. S. Geol. Survey, p. 389 (1890).

This is the first recorded attempt to secure a definite quantitative measure of the crust's rigidity from geological observations, and its amount is in striking contrast with many of the views previously noted, and would seem to limit rather narrowly the application of the hypothesis to ordinary geological problems. Gilbert does not say how the 600 cubic miles of load should be distributed.

The second edition of Osmond Fisher's well-known work* appeared in this same year, marshaling a numerous array of facts in support of isostasy, but not differing very essentially as regards this theory from the first edition.

Reyer, in 1892,† brings forward several objections against the theory of isostasy (*Onerar-hypothese*), while at the same time admitting that the earth's crust may be depressed if the sediments can first accumulate to a sufficient depth. Delta deposits may subside through the compression and squeezing seaward of their unconsolidated lower beds, without any sinking of the underlying solid crust. Subsidence is often more rapid than sedimentation, while enormous loads, especially volcanic accumulations, frequently fail to depress the crust beneath them. Eroded regions often sink in spite of denudation.

In the same year appeared McGee's‡ paper on the Gulf of Mexico, in which he regards the problem from the purely geologic standpoint, and presents that aspect of it with greater detail than any previous writer. This paper is the best presentation of the theory of isostasy as limited to the geological field, albeit carrying the idea of a sensitive crust to a somewhat extreme degree. Owing to its ready accessibility, only the writer's conclusions need be given here. They are as follows: "(1) The direct data of modern times indicate that deposition and isostatic subsidence are not only related sequentially, but that under favorable conditions they are quantitatively equal or sub-equal. (2) This measure of isostasy [the Gulf of Mexico] is consistent with the direct data, both quantitative and qualitative, yielded by other noteworthy deposition tracts of the

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* Physics of the Earth's Crust, 2d ed., 1889.

† Ursachen der Deformationen und der Gebirgsbildung. Leipzig, 1892.

‡ The Gulf of Mexico as a Measure of Isostasy, Am. Jour. Sec., 3 ser, Vol. XLIV, pp. 177–192.

globe. (3) The indirect data afforded by the Gulf indicate that isostatic (or consequent) movement alone is incompetent to explain the general continental oscillations recorded in the Neozoic deposits. Thus the Gulf of Mexico yields both maximum and minimum measures of isostasy."

McGee, like Dutton, distinguishes two kinds of vertical earth movement, viz.: "antecedent and consequent—the first including those great initial movements of debatable cause by which continents are lifted and sometimes deformed or drowned, and the second including the more restricted movements due to loading and unloading." It is not perfectly clear from his paper, wherein the vital distinction between the two lies, but it is to be observed, that in so far as he tends to *limit* the isostatic hypothesis to the more local movements, he cuts himself adrift from that general form of the theory which almost all physicists and geologists accept, and shows in this respect an opposite tendency to that exhibited in the paper of Gilbert last quoted from.

Willis, also in 1892,* speaking of the sediments which were laid down on the borders of the Palæozoic continent over the present area of the Appalachians, says that the "condition of isostasy prevailing in the earth's mass demanded that compensation should be made to the continental area for the load taken from it, and a deep-seated flow was set up landward, a movement sufficient to restore elevation to the continent, which might otherwise have remained at rest." Like Hall, he regards the sediments as the active cause of depression of the earth's crust, although differing from the latter in his explanation of the manner in which these strata were subsequently folded and elevated.

In 1893,† in a paper on the origin of mountain ranges, Professor Le Conte accepts in the main the general isostatic hypothesis as formulated by Dutton, and regards the earth's crust as yielding under the weight of sediments previous to the elevation of the latter into mountain ranges, and rising because of lightening by erosion. His discussion of this question is marked by a very obvious con-

* Mechanics of Appalachian Structure, 13th An. Rept. U. S. Geol. Survey, pp. 237–280.

† Origin of Mountain Ranges, Jour. Geol., Vol. I, pp. 543–573.

servatism and by the tendency to limit such isostatic adjustments to the larger inequalities of the earth's surface; yet it nevertheless reveals a considerable change of view from that held in 1886.

Geikie,* in the last edition of his Text-book (1893), dismisses the theory of isostasy in a rather summary manner. He says: "To suppose . . . that the removal and deposit of a few thousand feet of rock should so seriously affect the equilibrium of the crust as to cause it to sink and rise in proportion, would evince such a mobility in the earth as could not fail to manifest itself in a far more powerful way under the influence of lunar and solar attraction. That there has always been the closest relation between upheaval and denudation on the one hand, and subsidence and deposition on the other, is undoubtedly true. But denudation has been one of the consequences of upheaval, and deposition has been kept up only by continual subsidence."

An exceedingly important paper dealing with the problem from the physical side is the one on a series of transcontinental gravity determinations by Putnam † with the appended notes by Gilbert. According to Mr. Putnam, "the result of this series would . . . seem to lead to the conclusion that general continental elevations are compensated by a deficiency of density in the matter below sea-level, but that local topographical irregularities, whether elevations or depressions, are not compensated for, but are maintained by the partial rigidity of the earth's crust." ‡ Mr. Gilbert sums up his discussion of these observations and their bearing on the question of isostasy as follows: "The measurements of gravity appear far more harmonious when the method of reduction postulates isostasy than when it postulates high rigidity. Nearly all the local peculiarities of gravity admit of simple and rational explanation on the theory that the continent as a whole is approximately isostatic, and that the interior plain is almost perfectly isostatic. Most of the devia-

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* Text-book of Geology, 3d ed., 1893, p. 296.

† Results of a Transcontinental Series of Gravity Measurements, by G. R. Putnam.

Notes on the Gravity Determinations reported by Mr. G. R. Putnam, by G. K. Gilbert, Bull. Phil. Soc., Wash., Vol. XIII, pp. 31–76.

‡ *Loc. cit.*, p. 51.

tions from the normal arise from excess of matter and are associated with uplift. The Appalachians and Rocky Mountains and the Wasatch Plateau all appear to be of the nature of added loads, the whole mass above the neighboring plains being rigidly upheld. The Colorado Plateau province seems to have an excess of matter, and the Desert Range province may also be overloaded. The fact that the six stations from Pike's Peak to Salt Lake City, covering a distance of 375 miles, show an average excess of 1,345 rock-feet, indicates greater sustaining power than is ordinarily ascribed to the lithosphere by the advocates of isostasy." * Elsewhere the same writer remarks: "These results tend to show that the earth is able to bear on its surface greater loads than American geologists, myself included, have been disposed to admit. They indicate that unloading and loading through degradation and deposition can not be the cause of the continued rising of mountain ridges with reference to adjacent valleys, but that, on the contrary, the rising of the mountain ridges, or orogenic corrugation, is directly opposed by gravity, and is accomplished by independent forces in spite of gravitational resistance.

"While the new data thus indicate that the law of isostasy does not obtain in the case of single ridges of the size of a large mountain range, they agree with all other systems of gravity measurements in declaring the isostasy of the greater features of relief." †

A paper by Reade,‡ which appeared at the end of 1895, is noteworthy as evincing a change of view in admitting to a certain extent the theory of isostasy. Speaking of the pre-Permian Palæozoic strata, he remarks: "This loading doubtless squeezed and shifted laterally some of the deeply lying and more mobile matter underlying the normal crust, until a balance of stability was attained." He insists, however, that this theory, "so insisted upon by American geologists," is in no way applicable "to explain the compression, folding, and building up of great masses of sediment into mountain ranges."§

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* *Loc. cit.*, pp. 73, 74.

† Journal of Geology, Vol. III, pp. 331–334.

‡ British Geology in Relation to Earth Folding and Faulting, Geol. Mag., dec. IV, Vol. II, pp. 557–565.

§ *Loc cit.*, p. 564.

Dana, in the last edition of his "Manual of Geology" (1895),* points out that the sinking of coast-lines is often in excess of what would be demanded were the cause of sinking merely the accumulation of sediments. He leaves the theory practically open, however, and, like Geikie, devotes less attention to it than its interest and importance seem to demand.

The foregoing sketch, although not an exhaustive history of the theory of isostasy, has yet aimed to take note of all the more important utterances which have been published upon the question. No attempt has been made, however, to follow up the various suggestions and hypotheses which have from time to time been advanced as to the effect of masses of ice and snow upon the earth's crust, particularly during glacial times, among the most startling examples of which may be cited the hypothesis of Prof. Alexander Winchell,† in which the great volcanic outflows of the western states are regarded as having been squeezed out during Pleistocene times, by the weight of a continental ice-sheet some 5,000 feet thick. Such deductions have generally been marked by a more than ordinarily hypothetical character, owing to the great difficulty in the way of securing reliable data. The supposed masses, owing to their small specific gravity, must have exerted a relatively slight pressure upon the earth's crust, or, in other words, have constituted but a small departure from isostasy as compared with the sediments laid down in the past, and still covering vast areas of the earth's surface. If the deposition of these, and the maintenance of their present position above sea-level, have been factors of sufficient importance to cause an appreciable readjustment of the earth's crust, then we may hope to get from their study some quantitative scale to apply to the supposed effect of a great ice-cap. But if it can be shown that the rigidity of the earth's crust is not perceptibly diminished under such sedimentary loading, then the glacial aspect of the problem will require no further attention.

On the whole, the foregoing historical outline may be considered as showing that the isostatic hypothesis as ordinarily understood by

* pp. 377–379.

† Pressure of a Continental Glacier, Am. Geologist, Vol. I, pp. 139–143.

geologists, notwithstanding the power and brilliancy of its supporters, occupies a very unassured position, and that this uncertainty has not been diminished by the latest light thrown upon the subject of isostasy. It is, moreover, impossible to review the literature without being impressed by the contrast presented between the general vigor and dash of the supporters of isostasy and the apparent apathy shown by the advocates of rigidity. However assured the latter may feel in the strength of their position, attacks directed against it with such ability, and by men of such acknowledged prestige as Dutton and Gilbert, may be considered as calling for more searching criticism than they seem to have experienced.

It will be the purpose of the following section to see how far this isostatic hypothesis is applicable to explain the facts met with in the Great Valley of California, more particularly the subsidence of its floor during late geological times.

THE THEORY OF ISOSTASY AS APPLIED TO THE GREAT VALLEY.

The description of the Great Valley given in the preceding pages has shown that it is an area of closely associated sedimentation and subsidence. Such an area would probably be classed as a typical example of isostatic subsidence due to loading, by such geologists as consider the sinking of great river deltas and other restricted areas of deposition as due to the same cause; and, as we shall see, it was so regarded by Becker. But it has been shown that the hypothesis thus appealed to can not be looked upon as occupying an unassailable position at the present time, and it is accordingly unwise to shut our eyes to this fact and proceed to use the "doctrine of isostasy" as if it were a generally accepted theory in geological science. However beneficial the formulation of hypothesis may be as an exercise of the scientific imagination, it is a process not profitably resorted to when a given set of phenomena can be accounted for by the application of known laws.

With these thoughts in mind, it appears that the question of the fitness of applying the hypothesis of isostasy to the Great Valley may be approached by two distinct steps, which may be conveniently indicated by the two questions—(1) Is it necessary? and (2) Are there any facts which invalidate it? Having answered

these questions for the particular area under discussion, an attempt will be made in the succeeding section to carry the same general plan of investigation farther, and to arrive at more general results by admitting other regions into the discussion.

The Hypothesis Not Necessary.—There is probably no more obvious and general law in dynamical geology than the statement that the elevated regions are exposed to denudation, and depressed regions are areas of deposition whenever they are so situated as to receive sediment from an adjacent land mass. By the operation of forces of which we are profoundly ignorant, a portion of the earth's crust is elevated above the general level, while at the same time an adjoining portion may be depressed below it. A cycle of erosion, transportation, and deposition is initiated, whose activities, at first less energetic than the original disturbing forces within the spheroid, gradually equal and then surpass them in intensity, and finally reduce all again to the original mean level that preceded the beginning of the cycle. It is certain that isostasy can not account for the *initiation* of such a cycle. Being purely a theory of readjustment to a former state of equilibrium, it obviously can not be appealed to as causing an initial disturbance of such equilibrium. If we consider an original deformation of the lithosphere produced by some other or unknown cause, then it is possible to imagine isostatic adjustment as taking place by a series of secular oscillations of diminishing amplitude; but, as Woodward has pointed out, such a system would come with geologic rapidity to a state of final rest. Geology, however, gives little support to such a view of final peace and quietness. Mountain systems have risen and have been swept away, while many of the greatest mountain ranges and loftiest table-lands of the present day are, as is well known, of comparatively modern date; and it is manifestly impossible to regard their elevation as due to enfeebled remnants of oscillations which were set up once for all during the birth-throes of Archæan or pre-Archæan ancestors.

Without at present going further into these general questions, it would seem that we are justified in assuming the present activity of very energetic forces within the spheroid, capable of elevating and depressing both large and small areas of the earth's surface, and

which are, at least to begin with, independent of loading or unloading through transfer of sediment. Having at hand then a general law relating such movements with denudation and sedimentation, which is independent of the theory of isostasy, it remains to be seen how far it is able to account for the facts met with in the Great Valley. If it can do so fully and satisfactorily, then the isostatic hypothesis is, for this particular area, superfluous.

One of the most common arguments for isostasy is the frequently observed fact that sediments laid down in a subsiding area exhibit characteristics which show them to have been successively deposited in very shallow water. The conclusion is drawn that the subsidence must have just kept pace with the sedimentation. But a very little reflexion shows that such a conclusion is not justified, unless it be first established that the sediment was not supplied at a rate more than sufficient to keep up with the sinking. That such an overabundance of sediment has been furnished the subsiding valley through its late geological history, there is excellent reason to suppose. At the present time, such is certainly the case, for the Sacramento and San Joaquin Rivers annually carry large quantities of sediment into San Francisco Bay, where it is partly deposited, and partly swept out to sea by the strong tides setting through the Golden Gate, and dropped upon the bar lying off the entrance to the harbor. The occurrence of coarse gravels and "cobblestones" at a depth of over 2,000 feet, in the very middle of the valley at Stockton, shows that at that period of their history, these streams were vigorous transporters of material, close up to the point at which they issued from the valley (assuming that the outlet of the latter in Pleistocene times was practically where it now is), and must have carried large amounts of finer sediment out to sea as at present. There is accordingly nothing remarkable in the fact that the unconsolidated deposits revealed in the bottom of the Great Valley by borings were all successively deposited very close to sea-level. It is exactly what would be expected in any slowly sinking area which was at the same time supplied with sediment more than enough to make good the depression.

In strict accordance with the legitimate assumption made at the beginning of this section, it is not necessary to provide an explana-

tion for every isolated case of the subsidence or elevation of a restricted area of the earth's surface. We know that such movements take place, on a large and small scale, through the operation of a hidden mechanism to which we do not possess the key, and which, as far as we can see, is unaffected in its workings by superficial loading or unloading. Having seen that the subsidence of the Great Valley is not necessarily delicately adjusted to the amount of sediment available for deposit upon its floor, this is in itself enough to show the unnecessary character of the isostatic hypothesis, while the sinking itself can be looked upon as merely an example of one of those mysterious movements just referred to, which can not be *comprehensively* explained through the shifting of material on the earth's surface.

But the Great Valley does not seem to demand an immediate retreat to this refuge. There appears to be a possibility in this case of pushing the inquiry yet a step farther back, and arriving at at least a proximate cause for the movement which its floor has undergone. The forces which initiated the elevation of the Coast Ranges at the close of the Miocene were antecedent in their activity to the formation of the valley, and were consequently independent of any loading and subsidence of its floor. The movements then initiated have continued to the present time, and are, broadly speaking, orogenic in character. What effect can such orogenic movements have had upon the bottom of the adjacent valley? According to the ideas of mountain formation held by nearly all geologists, the effective force by which these ranges were folded and elevated, whatever its source may have been, was a lateral pressure acting along lines approximately perpendicular to the trend of the Sierra Nevada. This statement will apply to Reade's theory as well as to the ordinary contractional hypothesis. During this process of elevation and compression, the floor of the Great Valley must have acted as a strut, against which the thrust was exerted, and which perhaps transmitted it in part to the Sierra Nevada mass. We know that a little later, during Pliocene times, the Sierra Nevada also began to be elevated, a movement which partially culminated at the end of the Pliocene, but which seems to be still in progress. It is improbable that the crustal block form-

ing the floor of the Great Valley could have remained utterly unmoved by the vigorous orogenic forces at work on both sides of it. The natural question is, How was it affected? It was almost certainly bent into a shallow syncline—substantially the structure which it has at the present day. Had it originally been buckled upward into an anticline by the pressure applied to its edges, it is difficult to see how it could have later been changed into a syncline, since the orogenic movements have been progressively at work, and the valley floor consequently under a compressive strain all the time. The fact that the Coast Ranges and Sierra Nevada sweep around the southern end of the Great Valley, and join near latitude 35°, and that a similar junction of the bounding ranges terminates it on the north, also points to an original synclinal structure. For near where the ranges unite, the valley floor must certainly on the whole have been synclinally depressed, and these lines of weakness initiated at both ends of a long, narrow crust-block under lateral compressive strain, would be very likely to propagate themselves toward the middle portion of the valley, so as to give it its present shallow, basin-like form. It thus appears that there is no necessity to call upon the hypothesis of isostasy in order to account for the present form and condition of the Great Valley, but that, on the contrary, the latter presents no features which can not be explained through the activity of geologic processes less hypothetical in character than is the theory of isostasy.

Facts Opposed to Isostatic Subsidence.—That the floor of the Great Valley is not *perfectly* isostatic is sufficiently shown by the way in which the Sacramento, San Joaquin, and other of the larger streams, flow through the plain upon low ridges of their own construction. Similar evidence of a stronger kind is afforded by the alluvial fans which have been projected into the valley by the streams flowing down from the Sierra Nevada. Such a fan has been built up within the last fifty years by the Yuba River, near Marysville, whereby the latter town, formerly above, has now become below the river at high water. But by far the best examples of these structures are those which have been pushed out on the eastern side of the San Joaquin and Tulare Valleys by the San Joaquin, Kings, and Kaweah Rivers, and, further south, by the Kern

River, and which have already been described. That these heavy local accumulations of sediment can be piled up upon the plain, so as to crowd the San Joaquin River and lakes of the Tulare Valley over to the western side of the Great Valley, is not in accord with the idea that the valley floor is in a state of delicate adjustment, ready to compensate by subsidence for any additional load laid upon it. Had such an equilibrium existed, Tulare Lake could not have been formed by the alluvial accumulation which dams it on the north. On the theory of a sensitive crust, we should expect rather to have the main drainage of the Great Valley closer to its eastern side than to the western; for on this side has been the heaviest deposition, and, therefore, according to the theory, the greatest subsidence. Whether this would *actually* be the result brought about under the conditions supposed, is a matter that may be considered open to discussion. The main thing, to which attention is here directed, is the fact that the alluvial fans, the lakes, and the main streams, occupy exactly the relative positions, with regard to each other and to the borders of the valley, that they would have were the floor of the latter regarded as rigid under the load of sediment which has been laid upon it, or subsiding at a rate independent of that load.

If, then, the isostasy of the Great Valley be not perfect, there is only one other way in which we can conceive of the adjustment taking place. It is plain that if the theory of isostasy is to be adhered to at all, the idea of a gentle and regular subsidence must be relinquished for a movement that is more or less spasmodic in character. The sediments must accumulate until their weight is great enough to overcome the resistance, and when this happens, there will be a sudden settling down of the loaded area to its new isostatic bearings, to be followed by another period of quiet and preparation. But if this be the nature of isostatic adjustments, then it would seem that the fact, so much insisted upon by the supporters of the theory, of the great persistency of extremely shallow-water conditions of deposition from the bottom to the top of many sedimentary series, proves too much for their case. Considering for the present the Great Valley only, the well-borings, as far as the records go, show a rather striking regularity of character in the

deposits. They are all of distinctly fluviatile, or possibly shallow-lacustrine character, and indicate a rather gradual and gentle subsidence, with no marks of the catastrophic downward plunges of the crust required by the theory of isostasy when pushed (as above) to its logical conclusion.

In the Sacramento Valley, Diller has described some features which do not seem to be in full accord with the hypothesis of isostatic subsidence. About five miles east of the Sacramento River, at Red Bluff, the bed of Tuscan tuff is described as bending abruptly downward toward the west, beneath the newer formations of the valley.* The same tuff exposed in Iron Cañon, five miles north of Red Bluff, exhibits a well-defined transverse, or east and west, anticlinal arch, which is also well shown in the railroad levels in the valley.† These flexures of the younger deposits in the Great Valley, although they occur too close to its margin to be of the highest value as evidence, yet, as far as they go, seem to indicate that the valley floor is subjected to a compressive stress, whereas, in accordance with the isostatic hypothesis, it should be under tension; the tendency should be to smooth out all existing minor wrinkles, rather than to create new ones.

The same writer refers to a local subsidence at Cherokee Flat, on the eastern border of the Sacramento Valley, whereby "the finer essentially estuarine deposits over 300 feet in thickness, lap over to the eastward upon the ancient river and shore gravels mined at that place." ‡ This local subsidence must have taken place, or at least begun, before the accumulation of any of the finer sediments, and indicates a local movement independent of loading; for as river and shore gravels are formed at or above the local baselevel, subsidence must have taken place before finer estuarine deposits could be laid down upon them.

Becker,§ Ross Browne, || and Lindgren ¶ have all called atten-

* *Loc. cit.*, p. 414, also 8th An. Rept. U. S. Geol. Survey, p. 425.

† *Loc. cit.*, p. 433.

‡ *Loc. cit.*, p. 428.

§ Structure of a Portion of the Sierra Nev., Bull. Geol. Soc. Am., Vol. II, pp. 49–74.

|| Ancient River Beds of Forest Hill Divide, 10th An. Rept. State Mineralogist of Calif., p. 443.

¶ Two Neocene Rivers of Calif., Bull. Geol. Soc. Am., Vol. IV, pp. 297, 298.

tion to the fact that the vertical curves of the Neocene rivers do not correspond with the curves of erosion of the present streams, the latter showing a greater concavity. Becker considered this as due to a more prolonged erosion of their middle courses by the present streams, while the upper portions of the Sierra were protected by a Pleistocene ice-cap. But the work of Browne and Lindgren has shown that the cause of the difference is to be found in a deformation of the western slope of the range during an uplift " extending over a long period since Neocene times." Speaking of the Middle Yuba River, Lindgren says: " If the modern river curve shows such regularity, it would be natural to expect that that of the Neocene river, which represents a more advanced stage of base-leveling, should be still more so. But the plotted curve of the Neocene Middle Yuba River does not correspond to the normal curve of erosion. Instead, it appears to be composed of two curves with the convex side upward. I think this convexity, which can not be explained by differences in the resistance of the rock masses over which the river flows, must be due to a deformation of the surface during the uplift of the Sierra. The most pronounced departure from the normal curve of erosion results from the present steep grades of the Neocene channels near the valley. This is marked in both of the profiles given, and must, I think, be regarded as indicating a subsidence of the portion adjoining the sediment-filled trough of the Great Valley relatively to the middle part of the range, or a rise of the latter relatively to the former."

At the first glance, this result appears to be a rather striking confirmation of the isostatic hypothesis; but second thought shows that it is susceptible of a different interpretation. For if we regard the whole western slope of the Sierra and the floor of the Great Valley as a single orographic block, partly tilted, and very slightly flexed by tangential pressure, then the arching of the Sierra slope may be regarded as the geo-anticline corresponding to the geo-syncline of the valley floor. In such a case it would be natural to find an increased grade of the old stream beds near the edge of the valley, where the anticlinal passes into the synclinal curve, and the result would be in harmony with the continued activity of the orogenic forces during Pleistocene times. It is fairly certain that a

curve produced under conditions of ideal isostasy would be of a somewhat different character from that resulting from tangential pressure—or whatever force that may be which produces such broad, gentle flexures of the earth's crust. But it is doubtful whether we can ever arrive at such criteria, or, if found, apply them to an actual geological case. It does appear possible, however, to draw some conclusions from the position of this convex curve, and its relation to the newer formations on the valley's edge. If the Great Valley owes its present shape to isostatic subsidence, then the fact that the great source of the sediment has been the Sierra Nevada, and the probability that during Pleistocene times it has largely been laid down in the form of alluvial fans, would indicate that the heaviest deposition, and consequently the greatest subsidence, must have taken place on the eastern side of the valley, close to the foot of the range. The result of this would be a continual loading downward of the lower skirts of the Sierra, in such a way that the newer formations would successively overlap the older, and finally transgress onto the ancient upturned rocks of the "bedrock series" of the Sierra slope, while at the same time the convex curve shown by the river channels would be transferred further and further east. The portion of the Great Valley receiving sediment would steadily increase in area at the expense of the range from which the material was being derived.

But such is not the observed condition of the sediments on the lower flanks of the Sierra to-day. If we travel from the middle of the valley toward the Sierra Nevada, the Neocene strata soon emerge from the lower alluvium of the main valley, older and older beds coming successively into view. This successive emergence of the older beds is well shown on the Merced River, a tributary of the San Joaquin, draining the famous Yosemite Valley. Near Merced Falls, the base of the Tertiary series (supposedly Tejon-Eocene) rests almost horizontally upon the truncated Jurassic slates at an elevation of about 900 feet, while the younger Tertiary beds occur further west, and at lower elevations. Nor is this elevation recorded by the Tertiary rocks alone; for from Merced Falls westward, the more recent alluvial plain of the river is bordered, particularly on the north, by conspicuous bluffs, which mark the edges of an earlier

dissected Pleistocene plain. Near the falls these bluffs are very low, and swing in close to the river; but further west they attain an elevation of probably 100 feet or more, and are separated from the river by broad stretches of level alluvium. Upon surmounting the crest of the bluff, a similar level plain is revealed stretching back to the low rounded foot-hills. Such a terrace can hardly indicate anything else than a rise of this portion of the Great Valley's edge relative to the local baselevel of the Merced River, which is determined by the San Joaquin. Thus the lowest flanks of the range show evidence, not of a dragging down or subsidence, but of a gradual elevation up to very recent times. The result has been to confine more and more the latest deposits in the Great Valley to narrowing strips of flood-plain bordering the rivers, and to increase the area of the Sierra Nevada foot-hills at the expense of the level plain.

It seems fitting at this point to consider the application of the isostatic hypothesis to the Great Valley, made by Becker.* He considers that the elevation of the Sierra Nevada was not effected by a more or less simple tilting of a great crustal block, as is generally supposed, but by the cumulative result of a series of innumerable small northwest and southeast faults of Pliocene age, having their upthrows on the eastern side. The effective force for this faulting and elevation he supposes to have been derived from the isostatic subsidence of the sediment-laden valley floor, which produced not only a viscous flow of material underneath the rising Sierra mass, but supplied also the tangential force by which that elevation was mainly effected.

This hypothesis is plainly open to any objection that has already been brought against isostatic subsidence in the valley, when no particular cognizance was taken of the further mechanical consequences of such adjustment. But Becker's hypothesis, by following out these consequences, and attributing to the energy of the subsiding mass a certain mechanical result in the elevation of the adjacent mountain range, has made it possible to apply to it a rough quantitative test.

The accompanying diagram is intended to represent a transverse

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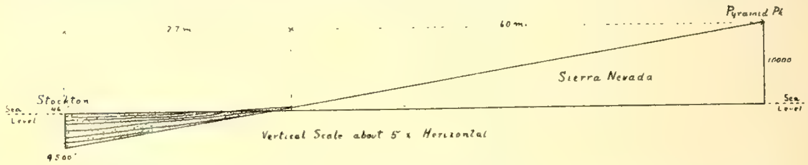
* *Loc. cit.*, p. 73.

section from the town of Stockton, which lies somewhat west of the middle line of the valley, to Pyramid Peak, near the crest of the Sierra. The section is not carried across the whole valley, as obviously only the eastern half of the latter could have been effectively concerned in elevating the Sierra Nevada crust-block, while the



western half was performing a similar office for the Coast Ranges. For the sake of simplicity, the general slope of the Sierra is carried down in a straight line under the valley sediments, reaching a depth of about 4,500 feet under Stockton. If we assume that this is the thickness of the sediments which were effective in causing elevation, then the diagram shows the great disparity between the effect and the supposed cause. But it may be that the subsiding valley sediments are much thicker than this, in which case they would have to attain a thickness of nearly 20,000 feet to become an effective counterweight to the Sierra mass. It is barely possible that the total undisturbed strata of post Jurassic age may attain a thickness of 20,000 feet beneath Stockton, but by no means all of these could be regarded as available for initiating the elevation of the Sierra in Pliocene times, that being the date Mr. Becker assigns to the faults. For this would imply a storing up of energy since the opening of the Cretaceous, whereas it is very improbable that any such pent-up forces should have failed to find relief in isostatic readjustment during the vigorous orographic movements at the close of the Miocene.

Thus far the discussion has been limited to the Great Valley and its immediate hydrographic basin, but the parallelism of the former with the numerous smaller valleys of the state, and with the larger one of the Gulf of California, is so striking, and so suggestive of genetic relationship, that it seems better to treat of it at this place, rather than in the general discussion later on. Such a general parallelism between coast line, mountain ranges, and valleys can mean only one thing, viz., that the latter have been formed or determined

by the orogenic uplifts of the region. These valleys may not always be synclinal in structure; some of the smaller ones may be eroded anticlines; but, with few exceptions, the stream-watered valleys of the state, having broad alluvial bottoms, are parallel with the principal mountain uplifts, and are determined by them. There is, of course, nothing remarkable in this. It is what occurs in nearly all regions of parallel folding. But it is of interest to show that the Great Valley of California is merely one member of a system of valleys, and that most of the latter have certainly not subsided isostatically.

The considerable valley in which the Bay of San Francisco lies, is, on the whole, as Professor Lawson has lately shown, a sunken area. It resembles the Great Valley in gathering its drainage both from its north and south ends, and in having a narrow western outlet, the present Golden Gate, cutting directly through a range of hills. The fact that the drainage from the Great Valley has always, as far as we know, flowed across this now submerged valley of San Francisco Bay and through the Golden Gate, is some indication that the two valleys have experienced substantially the same movements during the Pleistocene, and that the present submergence of the area covered by the bay is closely connected with the subsidence indicated in the middle portion of the Great Valley by the borings at Stockton. It therefore becomes important to decide, if possible, whether sedimentary loading can be regarded as the cause of the subsidence of the shores of San Francisco Bay. The latter is undoubtedly an area of active deposition, but it is believed that any geologist, even a believer in the theory of isostasy in its most extreme form, would acknowledge that in this particular case the amount of subsidence is in excess of that required by the theory. As Professor Lawson has shown, the subsidence is not limited to the immediate borders of the bay, but is discernible along the ocean coast, from near Pigeon Point on the south, to Russian River on the north, a distance of nearly 100 miles, and involving an area out of all proportion to that immediately under load of recent sediments. The bay itself presents a more conspicuously sunken aspect than the mere weight of sediments laid down within it can account for.

On the whole, then, it may be concluded that the maximum

subsidence in the middle of the Great Valley, and the subsidence of the bay region, stand in close relation to each other, but are not due to loading down by sediments.

The great longitudinal depression occupied by the Gulf of California and the Colorado Desert, offers some very interesting analogies with the Great Valley of California. According to Lindgren,* and Emmons and Merrill,† the long peninsula to the west of the Gulf has substantially the structure of the Sierra Nevada, rising toward the east in a very gentle slope, and then falling abruptly, in a great escarpment of several thousand feet, to the narrow strip of gently sloping mesa on the immediate Gulf coast. The area occupied by the Gulf, and by the desert valley to the north, is accordingly comparable, as regards structure, with the Basin Region to the east of the Sierra Nevada, and not with the Great Valley of California. But this is the more interesting, as showing a second way in which a long, narrow valley can be formed independently of sedimentary loading, by faulting instead of by gentle flexing of the crust. Into this valley the Colorado River has poured vast quantities of sediment from the waste of the great interior plateaus. Entering from the east side, like the San Joaquin and Kings Rivers, it has thrown a great delta across the Gulf, and finally cut the latter off completely from any communication with the northern portion of the valley. This severed northern end thus became a lake, comparable with Tulare Lake, and finally through complete desiccation was converted into the great Colorado Desert of to-day, portions of which are 275 feet below the sea.‡ The recency of these events, and the present activity of the processes through which they have been effected, are strikingly shown by the way in which the Colorado River occasionally makes breaches in its bank, and sends a portion of its water down the northern slope of its alluvial fan, forming in the desert the well-known New River and Salton Sea. Thus we have here a close parallel to the process which is going on in Tulare Valley to-day.

* Notes on the Geology of Baja California, Proc. Calif. Acad. Sci., 2 ser., Vol. I, p. 173.

† Geological Sketch of Lower California, Bull. Geol. Soc. Am., Vol. V, pp. 489-514.

‡ Preston, 11th Rept. State Mineralogist of Calif., p. 387.

Again, as in that valley, these are not the conditions that would be brought about by ideal isostasy. The great alluvial fan of the Colorado has been built up above sea-level faster than subsidence (if there be any actual subsidence) could carry it down, while, further south, the Gulf of California, which, down to the islands of Tiburon and Angel de la Guardia, is a portion of the continental platform, with no depths greater than 200 fathoms,* testifies to a depression that is in excess of any available load upon its floor. Thus in the north, the subsidence has been too small, and in the south, too great to be accounted for by the theory of isostatic adjustment to sedimentary loading, and must have been independent of it.

GENERAL DISCUSSION OF THE THEORY OF ISOSTASY.

The Data upon Which the Theory Has Been Made to Rest.—Undoubtedly the first suggestion of the theory of isostasy came from the observation that, as a general rule, the thicker masses of sediments laid down during the past geological ages have been deposited over subsiding areas, and at such a rate that subsidence and deposition have kept pace with each other. Thus accumulations many thousands of feet in thickness, which have been brought into view by the ever-recurring cycles of earth movement, reveal the fact that at no time during their deposition were they covered by any great depth of water. On the contrary, at frequent intervals, from the top to the bottom of such a series, we may see evidence that passing showers pitted the mud left bare by the tide, or that the animals of those times recorded their tracks on its surface.

The obvious and simple explanation of such conditions of sedimentation was found in the isostatic theory, which by making the load the cause of the subsidence, appeared to insure the delicate balance between deposition and sinking which the facts seemed to demand. But, simple as the explanation at first appears, it leads ultimately to greater complexity, by introducing a distinct class of earth movements, and by demanding a mobility in the earth's crust which seems to be opposed to astronomical and physical calculations, and to many geological facts.

* Emmons and Merrill, *loc. cit.*, p. 513.

If, as we are compelled to do, we admit that the earth's crust is subject to movements which are not due directly to superficial loading or unloading, and suppose that the subsidence in an area receiving sediment is such an independent movement, then the sole condition necessary, to insure the continued laying down of shallow-water deposits, is that the supply of sediment should be locally equal to, or *in excess* of, the amount necessary to make good the sinking. As the shallow-water sediments, upon which the observations have been made, are off-shore deposits of more or less coarseness, or have been laid down in partially inclosed seas, there is nothing at all improbable in supposing that the sediments were usually furnished in ample abundance to maintain shallow-water conditions. Nor, on the other hand, is this view of subsidence and sedimentation in the least discordant with the known fact that deeper-water conditions, with the formation of massive limestones, have frequently succeeded arenaceous or argillaceous sediments, while such a sequence is not so readily accounted for by the ordinary theory of isostasy. The geologist might, with equal reason, argue that the widespread subsidence of the bottom of the Pacific Ocean, postulated by Darwin's theory of coral reefs is a result of the weight of the coral accumulations, inasmuch as the latter have just kept pace with it, as to insist upon isostatic subsidence to account for continuous shallow-water conditions of sedimentary deposition. The sediments could no more have risen considerably above sea-level than can the coral polyps of the present day, and that they did not always keep pace with the downward movement is shown whenever a deeper-water deposit succeeds one of shallow-water origin.

Turning now to what McGee calls the direct data for the theory of isostasy, we are brought to the examples of subsidence presented by our modern areas of deposition, more particularly in the accessible deltas of great rivers. Borings in such deltas have almost invariably shown indubitable evidence of subsidence, but it is to be remarked that this is not necessarily a subsidence of the underlying consolidated strata forming the earth's crust at that point. The work of Professor Hilgard, on the mud-lumps of the Mississippi, shows that at least a portion of such local subsidence may be

accounted for by a squeezing out of some of the lower unconsolidated layers by the pressure of the superincumbent mass, and indicates that the decomposition of vegetable matter, and molecular condensation, may be responsible for a part of the superficial subsidence. On the whole, however, it seems to be a well-established fact that most of the great deltas of the world are built up on subsiding areas; and, it may be added, necessarily so, for a rising area would obviously tend to divert the seat of deposition to another point, while an area which was neither rising nor sinking would soon be filled up to the baselevel, and the river would then carry its load further on to a more commodious place of deposition. Viewed from this aspect, there is nothing in the subsidence of a delta that requires the hypothesis of isostasy. The drainage of a great continental area will converge toward that portion of the adjacent sea-coast which is subsiding, and will continue to deposit its burden of sediment at that point as long as the movement continues. Moreover, deltas are conspicuously regions of superabundant sediment. Not only does the river make good by its deposits the subsidence of the earth's crust, but it carries the surplus further on, and pushes its delta seaward. Thus the Mississippi River, during later geological times, has pushed its delta from Cairo out to its present termination in the Gulf of Mexico, an extension that is not compatible with the idea of *pari passu* local sinking under load, but which indicates a subsidence of more general extent, and independent of such local loading, inasmuch as the maximum effect has been, not near Cairo, at the original point of loading, but to the south of it—probably in the deep hollows of the present Gulf of Mexico. The river did not stop to build up a thick mass of delta accumulations at Cairo, as it should have done according to the theory of isostasy; but, attracted onward by the independent subsidence to the south, it has covered the floor of the valley with relatively thin deposits only, and advanced persistently out into the Gulf.

Such subsidences of sediment-laden areas as we have been considering are generally made manifest by an encroachment of the sea upon adjacent portions of the land which are not receiving sediment. In some cases this subsidence appears to be in excess of

what the mere weight of the neighboring sediments would demand, as pointed out by Dana for the Atlantic seaboard, and suggested in this paper for San Francisco Bay. But even if this be not so, it is difficult to conceive of subsidence, due to a load of sediment, being extended to any distance outside of the immediate area of deposition, unless we assign to the materials of the earth's crust a degree of tensile strength in excess of that exhibited by the best of building stones, in which it is notably small. A pile of shot, placed upon a sheet of india-rubber, resting upon a viscous liquid, might exhibit a subsidence greater in area than the portion immediately covered by the shot; but it is hardly to be expected that the earth's crust, composed of materials which, as far as we know, are of very slight tensile strength, should behave as does india-rubber.

McGee has stated that most of the great historical earthquakes not connected with "vulcanism or orogeny" have "affected tracts of rapid deposition," and that commonly after the tremor the land stood *lower* than before. Like so much connected with the theory of isostasy, there is a seductiveness about this generalization which is apt to lead one astray. By excluding the earthquakes possibly connected with "vulcanism or orogeny," we are practically limited, as far as the land is concerned, to the low-lying plains, which are generally areas of subsidence, or are covered by recent sediments. And when, further, Milne tells us that "earthquakes chiefly occur in volcanic and mountainous regions,"* that they are particularly abundant along coasts which slope down at a high angle to great depths,† that "many earthquakes occur in mid-ocean," ‡ and that "earthquake and volcanic regions are situated on areas where there is evidence of rapid elevation,"§ the foregoing generalization rather loses its force. When we consider too, that the rich alluvial plains and low-lying deltas have been in all historical times the portions of the globe most densely populated, and that for this reason earthquakes in such tracts have resulted in appalling destruction of life and human works, it is not surprising that so many of

* Earthquakes, p. 227.

† *Ibid*, p. 228.

‡ *Ibid*, p. 228.

§ *Ibid*, p. 278.

the "great earthquakes" of history are said to have originated in such alluvial plains and deltas.

But even if it were a true generalization, it is not at all clear why earthquakes should accompany a subsidence taking place because of loading, any more than that they should be associated with a subsidence, under a load it is true, but due to some other cause.

Two Classes of Earth Movements.—Both Dutton and McGee, perceiving that the greater vertical, or epeirogenic, oscillations of the earth's crust do not admit of explanation through superficial loading or unloading, were led to distinguish between the two classes of movements. According to McGee, the greater movements of debatable cause are "antecedent movements," while the more restricted oscillations due to loading and unloading are "consequent movements." McGee would limit the term *isostatic* to these consequent movements. But to this limitation the physicist can take immediate exception. For, taking the simple definition of isostasy as stated by Dutton, it is obviously impossible that the earth's crust should be in such delicate equilibrium as to respond to superficial transfer of sedimentary material, and yet over larger areas be subject to vertical movements many thousand feet in extent, which are *not* isostatic. In other words, if the greater movements by which continents are upheaved or depressed are not in the nature of true isostatic adjustment, then they constitute a defiance of isostasy, so great and so glaring that it becomes absurd to consider the possibility of sedimentary deposits having any effect upon the solid crust beneath them. If, then, we can speak of isostasy at all as having any bearing upon geological science, then we must look upon these great epeirogenic movements as isostatic, and as they are obviously not caused by loading and unloading, then we are driven to the final conclusion that changes calling for isostatic adjustment of the outer crust of the lithosphere must at times take place within the latter, quite independently of the superficial results of erosion and deposition. The attempt to make two distinct classes of the vertical movements of the earth's crust is an unphilosophical one, and it is at least misleading to call the more restricted movements isostatic to the exclusion of the greater. It is these

greater deformations of the crust which many geologists would allow to be isostatic in character, while vigorously protesting against the idea of delicate adjustment to sedimentary loading, to which McGee would restrict the term isostasy.

The Bearing of Recent Pendulum Observations.—The recent gravity determinations recorded by Putnam and discussed by Gilbert appear to tend toward this larger view of isostasy, indicating as they do that the earth's crust rigidily upholds masses far greater than the advocates of isostasy had formerly been willing to admit. In his last paper, however, Mr. Putnam* finds gravity slightly in excess near the Gulf coast as compared with interior stations. This is interpreted by him as indicating a slight retardation in reaching a state of perfect isostasy. The data are too meager to draw any very definite conclusions as to whether the sediments of the Mississippi are the cause of subsidence. Such observations would need to be repeated in far greater number, not only for the Mississippi delta, but for other areas of active deposition and subsidence before we could be entitled to draw final conclusions from them. In the present instance the stations are so few in number, and the differences in gravity between the coast and interior stations so slight, that they do not seem to give any definite testimony in favor either of independent or "isostatic" subsidence. Moreover, confidence in the result, where such small differences are at stake, is impaired by the uncertainties involved in the theoretical reductions of the observations to a standard. For example, the difference between two sets of observations at Austin, so reduced, is .002 dyne, while the difference between the observations at the coast station at Galveston and one set of the inland observations at Austin is only .001 dyne. Moreover, *all* the observations show a theoretical *defect* of gravity, averaging, according to Bouguer's reduction, .0518 dynes, and according to Faye's, .038 dynes. This would rather indicate that the whole region has subsided more than isostasy demands.

Highly interesting in this connection are the pendulum observations which have been carried on in Europe during the last few years by von Sterneck † and others. These observations reduced,

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*Am. Jour. Science, Vol. CLI (1896), pp. 186–192.

† Rev. in Neues Jahrbuch f. Min. u. Pal., 1896, Bd. I, s. 234–239.

according to Bouguer's formula, which postulates high rigidity, appear to indicate that, as a *general* thing, gravity is in excess in the low-lying plains, and in defect in the mountainous regions. Many curious and unexplained facts come to light, however. For example, the boundaries between the regions of excessive and defective gravity do not always correspond with those separating the plains from the mountains. One slope of a mountain chain frequently shows a marked excess of gravity, while, on the other side of the summit, the reverse is the case. Stations situated in level plains, and along valleys, often show conspicuous differences in the force of gravity, this difference frequently being equivalent to the attraction of a plate of rock 60 m. thick for every km. of distance apart. In the flat plains, rivers are separated from each other by regions of somewhat less excess of gravity.

These results, as far as they go, are a shade in favor of the theory of isostasy, but there are too many unexplained anomalies to render the conclusions very decisive. Von Sterneck himself frequently emphasizes their provisional character. For comparison with the work of Putnam, it is interesting to note the general *excess* of gravity in the low plains of Europe, and the quite conspicuous differences between stations which ought, apparently, to show none.

Facts from the California Coast Bearing upon Isostasy.—We owe to the work of Prof. A. C. Lawson* the description of three portions of the coast of California which are extremely interesting in their bearing on the question of isostasy, viz.: Catalina Island, Seven Mile Beach, and the valley of the Eel River.

It is evident that if restricted areas of the earth's surface be capable of subsiding independently of any load of sediment that may be laid upon them, then there should be the possibility of finding some such subsiding area, which, owing to some special environment, has not been made a receptacle for sediment. Such areas might be looked for in the deeper ocean-bottoms, out of reach of ordinary mechanical sediments. That local depressions occur at abyssal depths is a well-known fact and has been emphasized by the recent announcement of the deepest soundings yet made occur-

* Bulletin of the Dept. of Geol. of the Univ. of Calif., Vol. I, pp. 115-160 and 241-272.

ring in such small isolated basins.* But there is nothing to show that these depressions are actually subsiding. We are accordingly limited in our search to those portions of the ocean-bottom that are adjacent to land, in order that their movements may be recorded by the relations of some subaerial land-mass to the general sea-level. But as in general the subsidence of a restricted portion of the coast means a conveyance of sediment to that point, the favorable conditions desired can rarely be found. It is this which makes the study of Catalina Island so interesting. As shown by Professor Lawson,† this island has subsided, while the strand of the mainland, twenty-five miles to the north, has risen 1,240 feet, and the island of San Clemente, twenty-five miles to the south, has risen 1,500 feet. This subsidence can not be regarded as the result of sedimentary loading, as no large rivers deliver their sediments into this basin, and the water about Catalina Island is remarkably blue and transparent, with none of the discoloration which is noticeable for miles outside of the Golden Gate. The movement, too, is out of all proportion to any conceivable weight of sediment that may have been deposited upon the sea-bottom, within the subsiding area. We have here, then, a striking example of the subsidence of a restricted area of the earth's crust which is not due to superficial loading.

At Seven Mile Beach, on the ocean side of the San Francisco peninsula, Professor Lawson ‡ has described Pliocene strata composed of arenaceous beds of shallow-water origin, having an aggregate thickness of over 5,000 feet. "The basal bed is a stratum of partially carbonized forest material," which "rests directly on a seemingly even surface of volcanic rocks which are of Mesozoic age." The theory of isostasy fails to explain such a sequence of events as is here recorded. The forest-bed can not be regarded as being of sufficient weight to depress its basement below sea-level, and there was probably a local subsidence which was independent of sedimentary loading, and which carried the forest-bed down below sea-level, and allowed it to be buried beneath marine sediments a mile in thickness. It must be borne in mind, however, that the

* Nature, Vol. LIII, p. 392 (1895).

†*Loc. cit.*, p. 135, *et. seq.*

‡*Loc. cit.*, p. 142, *et. seq.*

initial subsidence may have been connected with the general epeirogenic movements of Pliocene times; but if so, it was certainly not due to loading, although it may have allowed the accumulation of a few hundred feet of sediment before the true local subsidence set in.

Perhaps more conclusive in its testimony is the Wild-cat Series * of Pliocene rocks near the mouth of Eel River, composed of soft clays, sandstones, and conglomerates, resting unconformably upon Mesozoic sandstones. These strata, according to Professor Lawson, were accumulated in a local basin to a thickness of over a mile. Parts of the basement of the series, formerly depressed to that depth below sea-level, now stand about 1,600 feet above it. As the general depression of this portion of the coast in Pliocene times was from 1,600 to 1,700 feet (possibly 2,100 feet) lower than at present, the greater part of the subsidence which allowed of the accumulation of the Wild-cat Series must have been purely local, and the Mesozoic basement, as at Seven Mile Beach, seems to have gone down in obedience to some other force than that due to the weight of the sediments.

Mountain Building and the Theory of Isostasy.—A full discussion of the relation of isostasy to mountain formation would carry us far beyond the limits of the present paper, but, on the other hand, no treatment of the isostatic theory can be complete without some reference to this special application of it. Of all the facts which have been adduced in behalf of this theory, none, it seems to the writer, afford it so much support as the phenomena of mountain origin, as far as we know them, and it may be added that none have been less insisted on. The generalizations of Le Conte, Reade, and others, seem to have shown that the future birth of a mountain range is presaged by the laying down of a great thickness of coarse, off-shore sediments, the deposition being accompanied by a *pari passu* subsidence. But the significant feature of the process is the apparent fact that the accumulation of such a cylinder-lens of sediment can exert so potent an influence upon the earth's crust as to determine along that line the formation of a mountain range. This points to a sympathetic relationship between the movements of the underlying solid crust and the weight of sediments that is not con-

* Lawson, *loc. cit.*, p. 255, *et. seq.*

ceded by the advocates of rigidity under load. The latter are required to account for (1) the coincidence of a zone of subsidence running parallel with the continental margin, and (2) the final upheaval of these sediments into a mountain range. This makes a rather strong case for the upholders of isostasy, but not, it is believed, an impregnable one. It would be far stronger were continents invariably bordered by great mountain ranges, but such is by no means the case, as can be seen by reference to any good atlas of the world. Irregularities comparable to mountain chains exist, moreover, as we know, in the deep oceans, far from any existing land-mass. Then, too, there are not wanting eminent geologists who deny that the process of mountain-building is anything more than a very superficial one, not essentially involving the solid crust. Thus Reyer,* as a preliminary to presenting his gliding theory, refers to cases near Christiania, and in the Wesergeberge, where the folded strata rests upon basements which have not shared in their corrugation.

Without accepting Reyer's extreme view, it does seem that the effect of heavy accumulations of sediment upon the underlying crust by the rise of the isogeotherms, has been frequently exaggerated. It is quite commonly assumed that their rise softens the crust and metamorphoses the lower sediments; but, in fact, we find no signs of such metamorphism even in the oldest sediments, no matter how deeply buried, as long as they have escaped vigorous crumplings and igneous intrusions.

The actual elevation of the mountain ranges is a thing difficult to reconcile with the idea of delicate isostasy; for if strata spread out in a broad sedimentary lens are competent to depress the earth's crust, how can the same sediments, when compressed with no loss of mass to a smaller base, maintain their elevation above the geoid? They could do so if a large proportion of the sediments (supposedly lighter than the underlying material) subsided to a sufficient extent to buoy up the projecting mountain-mass above them. But such a structure, as far as the writer is aware, has never been recognized. Mountains in many cases reveal the base-

* Ursachen der Deformationen und der Gebirgsbildung. Leipzig, 1892, p. 23.

ment upon which the sediments were deposited, often elevated above its original position; in other cases it has been replaced by a great batholitic intrusion of plutonic rock ; but no case is recalled in which the sediments themselves can be shown to have been forced down to serve as a buoyant float for the superincumbent mass.

If we adopt the hypothesis of Fisher,* that the earth's crust is a sharply differentiated, solid shell, floating upon a heavier interior magma, and assume that the entire thickness of this crust is involved in the orogenic corrugations, then the question may be answered. For by the local thickening-up of this crust under lateral compression, and its downward protrusion into the fluid magma, the mountains might be buoyed up, and the sediments themselves elevated instead of depressed. But there are many objections to this view, and the modern tendency is rather to regard the earth as substantially solid, with no hard and fast line between crust and interior. Moreover, the hypothesis of a greatly thickened *solid* crust directly beneath a mountain range is not easily brought into accord with the frequent occurrence of plutonic intrusions along the axis of the range, which seems to indicate a thinning rather than a thickening of the crust.†

Reversal of the Movements of Subsidence and Elevation.—As is well known, areas receiving sediment neither subside indefinitely, nor yet come to a state of final rest, but are ultimately elevated above sea-level and exposed to erosion. Likewise, denuded areas at length cease to rise, and then sink down, and become covered by new sediments. This reversal of movement has been frequently cited against the theory of isostasy, and appears still to form an unanswered objection. Probably the most striking actual case of such movements is that described by King ‡ eighteen years ago in western United States, where, after the accumulation of 40,000 feet of Palæozoic sediments, the relative positions of land and sea were reversed by a great fault, and 25,000 feet of Mesozoic strata deposited upon the old denuded Palæozoic surface then changed into

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* Physics of the Earth's Crust, 2d ed., pp. 183, 184.

† Le Conte, Elements of Geology, 2d ed., p. 261.

‡ Explor. 40th Parallel, Vol. I, p. 731.

sea-bottom. "The marked and peculiar feature in this occurrence is the fact that the region which went down was the region which had been unloading during the entire Palæozoic." * Such a movement, according to King, belongs to an entirely different class from those which are said to be isostatic in character—a proposition which has been shown to be fallacious. The event here recorded, inasmuch as the movement was local and differential, not due to a general continental uplift nor complicated by great orogenic foldings, stands in conspicuous opposition to the theory of isostasy as applied to restricted areas of the earth's crust.

General Conclusion.—The considerations presented in the foregoing paper indicate that, while the greater inequalities of the earth's surface, such as the continental arches and the oceanic depressions, may exist by reason of isostasy, the mass of available evidence is opposed to the view that denudation and sedimentation are able to produce movements in the earth's crust, as direct consequences of the weight of the material shifted. Not only do such superficial processes seem inadequate to initiate deep-seated crustal movements, but, as far as we can see, the movements, even when initiated through other causes, are as indifferent to such processes as is a slumbering volcano to the changes wrought by human tillage upon its flanks.

Geological Laboratory,
University of California, April 13, 1896.

* *Loc. cit*, p. 731.

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